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PREPROCESSING ELECTRONIC SATELLITE OBSERVATIONS

by Joseph E. Gross III

Prepared by
OHIO STATE UNIVERSITY
Columbus, Ohio
for

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for

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PREFACE

This project is under the direction of Professor Ivan I. Mueller of the Department of Geodetic Science, The Ohio State University. Project Manager is Jerome D. Rosenberg, Geodetic Satellites, Code SAG, NASA Headquarters, Washington, D.C. The contract is administered by the office of University Affairs, NASA Headquarters, Washington, D.C.

Reports related to NASA Contract No. NGR 36-008-093 and published to date are the following:

<u>The Determination and Distribution of Precise Time</u>, Report No. 70 of the Department of Geodetic Science, The Ohio State University.

<u>Proposed Optical Network for the National Geodetic Satellite Program</u>, Report No. 71 of the Department of Geodetic Science, The Ohio State University.

<u>Preprocessing Optical Satellite Observations</u>, Report No. 82 of the Department of Geodetic Science, The Ohio State University.

<u>Least Squares Adjustment of Satellite Observations for Simultaneous Directions or Ranges, Part 1 of 3</u>: Formulation of Equations, Report No. 86 of the Department of Geodetic Science, The Ohio State University.

<u>Least Squares Adjustment of Satellite Observations for Simultaneous Directions or Ranges, Part 2 of 3</u>: Computer Programs, Report No. 87 of the Department of Geodetic Science, The Ohio State University.

<u>Least Squares Adjustment of Satellite Observations for Simultaneous Directions or Ranges, Part 3 of 3</u>: Subroutines, Report No. 88 of the Department of Geodetic Science, The Ohio State University.

<u>Preprocessing Electronic Satellite Observations</u>, Report No. 100 of the Department of Geodetic Science, The Ohio State University.

ABSTRACT

The purpose of this report is to present a detailed description of the preprocessing procedures currently used in the reduction of electronic data from geodetic satellites. The preprocessing procedures described are those used by the various agencies as of 1 January, 1968.

This report also presents a general, non-technical description of the four major electronic satellite tracking methods currently used for geodetic purposes.

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1. INTRODUCTION

One of the purposes of the National Geodetic Satellite Program is to store the data obtained from geodetic satellites in a central location, where it may be utilized by qualified personnel involved in geodetic research. In accordance with this purpose, the Geodetic Satellites Data Service (GSDS) was established within the National Space Science Data Center at Greenbelt, Maryland. A large amount of data has now been obtained by the various agencies involved in the National Geodetic Satellite Program, and is deposited in the GSDS. However, difficulty has been experienced in the utilization of this data because of an insufficient knowledge of the preprocessing procedures and the corrections applied to the data before submission to the GSDS.

The primary purpose of this report is to present a detailed description of the preprocessing procedures currently used in the reduction of electronic data from geodetic satellites. The specific corrections applied to the data are also given. A knowledge of the procedures listed herein should aid in the proper utilization of data obtained from the GSDS. This report also presents, in a non-technical manner, a general description of the four major electronic satellite tracking methods.

The preprocessing procedures described are those in use by the various agencies as of 1 January 1968, and therefore deal with information obtained prior to the launch of GEOS B. However only minor changes in format are expected as a result of GEOS B data; the basic procedures should remain as stated herein. Most of the information necessary to document these procedures was obtained in interviews and subsequent communication with the following personnel:

<u>Army Map Service</u>
- Mr. Eric H. Rutscheidt
- Mrs. Marvel Warden
- Mr. George Dudley

<u>Goddard Space Flight Center</u>
- Mr. John H. Berbert
- Mr. Thomas S. Johnson
- Mr. Douglas H. Rose

<u>Army Engineer Topographic Laboratories</u>
- Mr. James T. Reilly (presently with The Ohio State University)

<u>Naval Weapons Laboratory</u>
- Mr. Steven J. Smith
- Mr. Robert Hill

<u>Applied Physics Laboratory/Johns Hopkins University</u>
- Dr. Robert R. Newton
- Dr. William H. Guier

<u>Smithsonian Astrophysical Observatory</u>
- Mr. Carlton G. Lehr
- Mr. Piero Brovarone
- Mrs. Beatrice Miller

Wolf Research and Development Corporation
Dr. Samuel J. Moss

RCA Service Company
Mr. Horace C. Parker

The contents of this report were verified as being accurate by the above personnel, whose assistance is greatly appreciated.

2. GEODETIC SECOR SATELLITE SYSTEM

2.1 GENERAL SYSTEM DESCRIPTION

2.11 Introduction

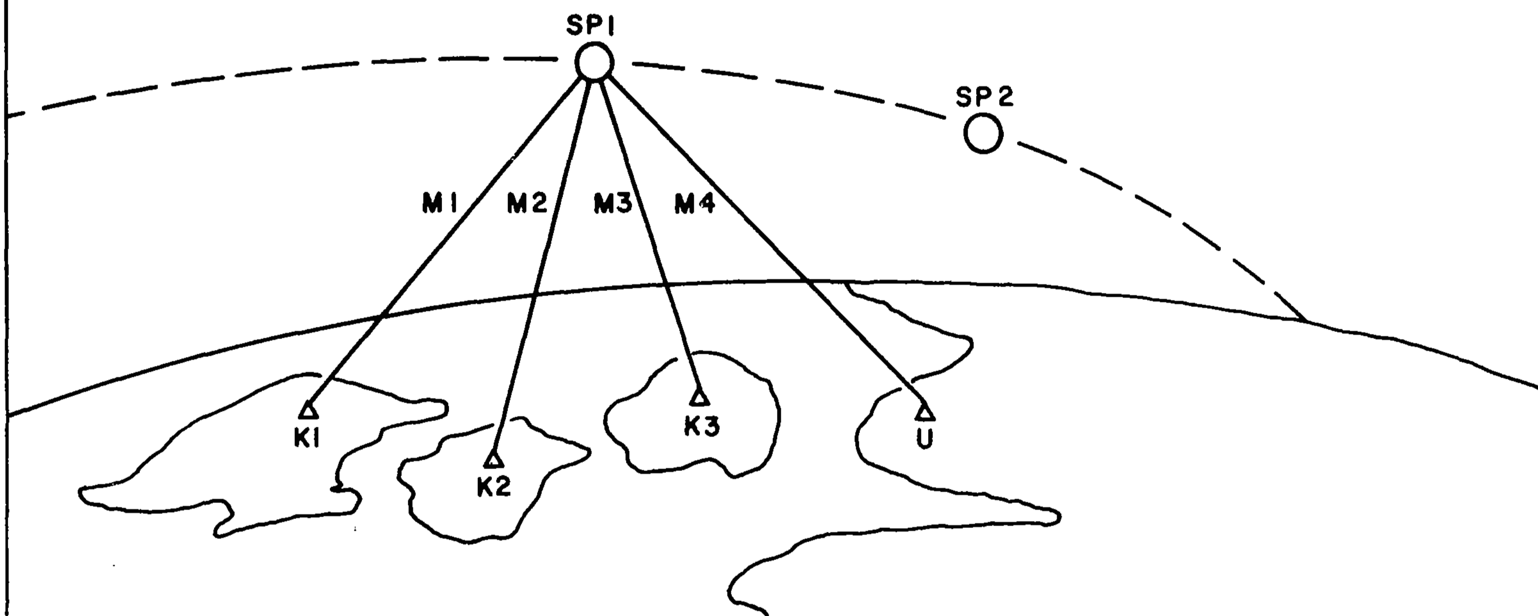
SECOR, an acronym for Sequential Collation of Range, is basically an electronic distance measuring system in which four ground stations sequentially interrogate a satellite-borne transponder. The system operates on the physical principle that modulation of an electromagnetic wave propagated through space will undergo a phase shift proportional to the modulation frequency and the distance traveled. The system was developed by Cubic Corporation and was put into operation by Army Map Service in 1964.

2.12 Principles of Operation

2.121 The purpose of SECOR is to extend geodetic control for inter-continental ties. This is usually not feasible by conventional means, due to the great distances involved.

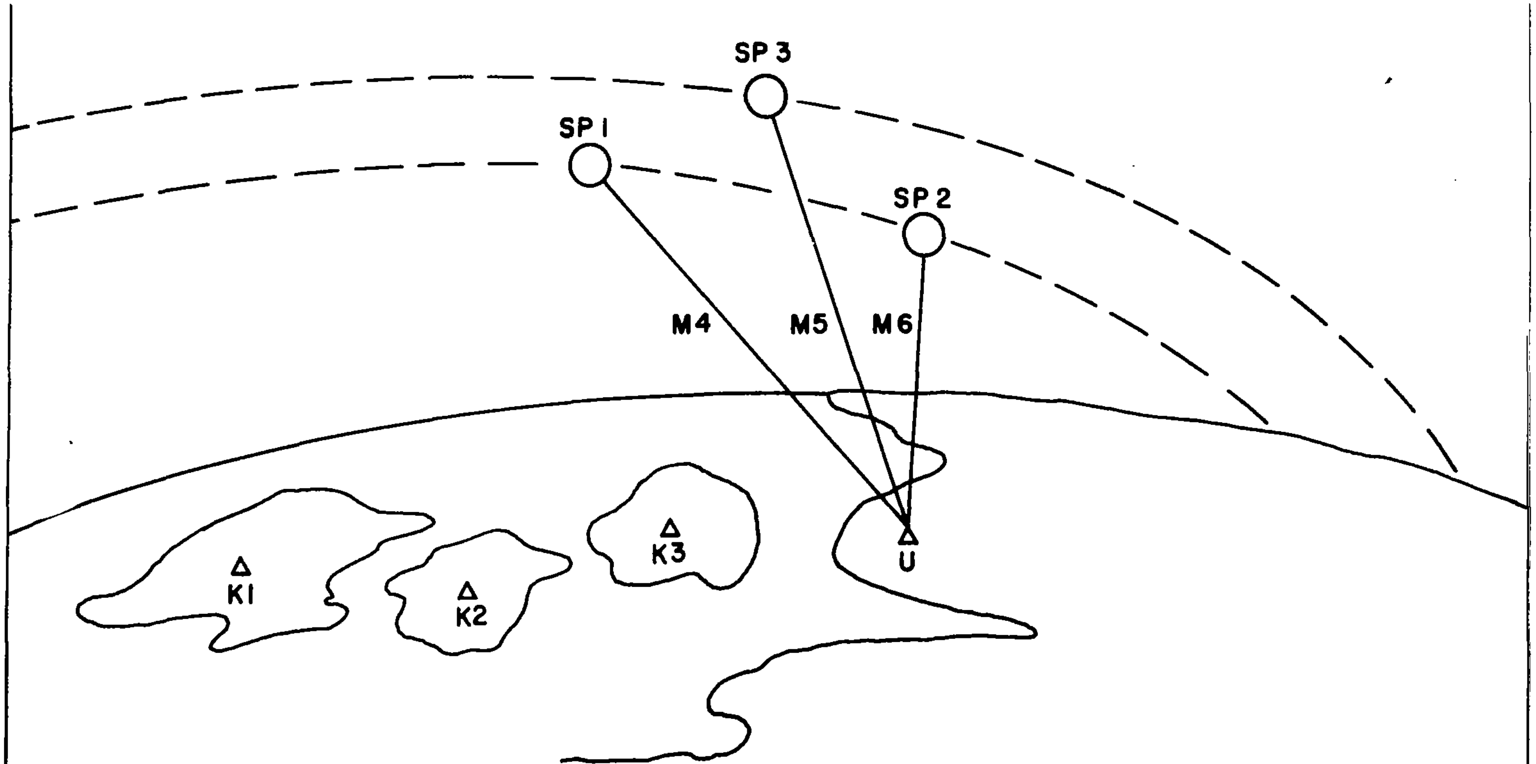
The geodetic technique applied in control extension is that of trilateration. Geometrically, we can consider a range from a ground station to the satellite as determining the surface of a sphere of radius equal to the range, and with its center at the ground station. Simultaneous ranges from the three known ground stations will determine three spherical surfaces which intersect at a common point, the point being the satellite's position at that time. If this is repeated for at least three positions of the satellite, the position of an unknown station which was ranging simultaneously can be determined as shown in Figures 2.1a and 2.1b. Naturally, the geometry of this situation will not allow a solution if the three satellite positions are in the same plane; therefore, at least two orbital passes of the satellite are needed. The above figures present only the simplest geometry necessary for solution. In practice, many positions of the satellite are used to determine the position of the unknown station and a least squares adjustment provides the means for obtaining an accurate solution. Once the position of the unknown station is determined, any one of the stations may be moved to a new location and the process is repeated, thus extending control.

The method of position determination described above is known as the Simultaneous Mode. This method has the primary advantage that the solutions are independent of the orbital parameters of the satellite, which eliminates the need for satellite ephemeris data and orbit theory applications. However, a disadvantage is that the satellite must be tracked simultaneously by all stations, thus imposing a geographical limitation on the distance



From the 4 ground positions K1, K2, K3, and U, simultaneous distance measurements M1, M2, M3, and M4, to the satellite are made. The space position SP1 can then be computed by the intersection of the 3 spheres of radius M1, M2, and M3 whose centers are known positions. Space position SP2 is determined in the same manner, and again a measurement is also made from the unknown position.

Figure 2.1a. Satellite Position Determination by Simultaneous Mode.



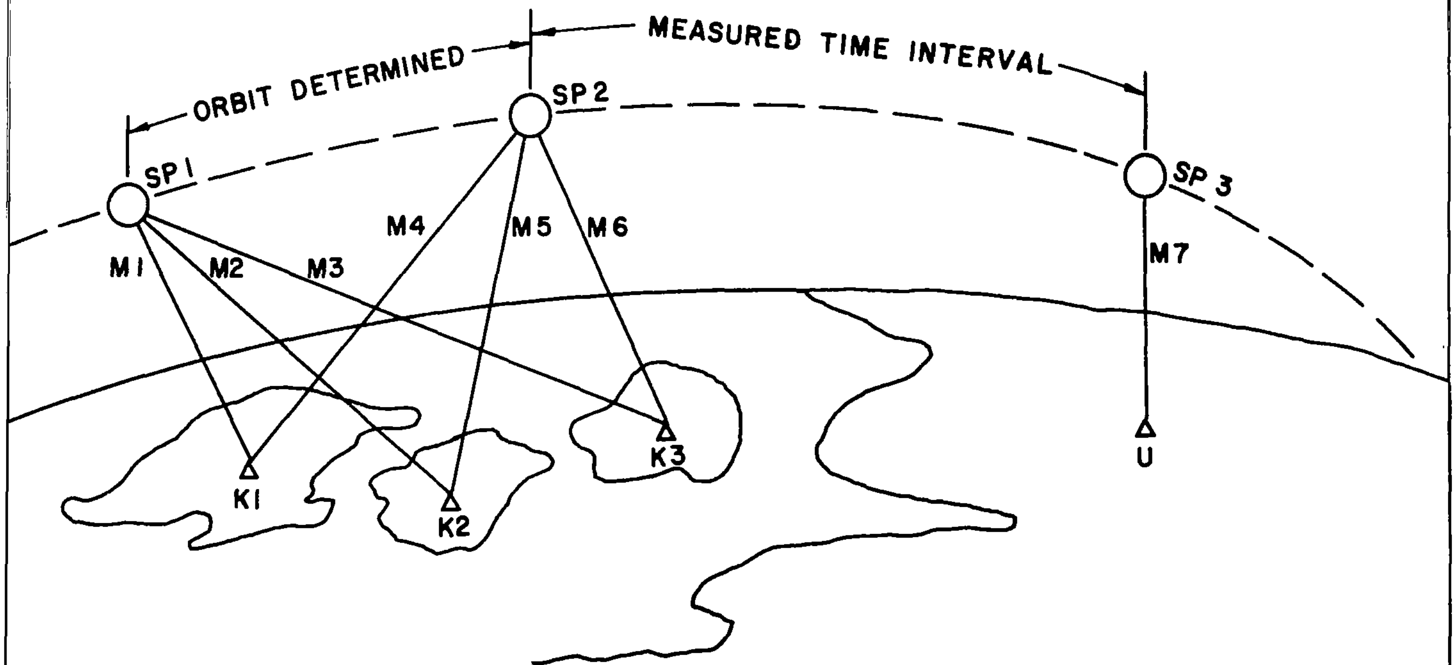
SP3 is determined in the same manner as SP1 and SP2 but during a different pass of the satellite. This is necessary so that SP3 does not lie in the plane of SP1, SP2, and U. The coordinates of U are then determined by the intersection of the 3 spheres of radius M4, M5, and M6 whose centers (SP1, SP2, and SP3) are computed positions.

Figure 2.1b. Station Position Determination by Simultaneous Mode.

between stations.

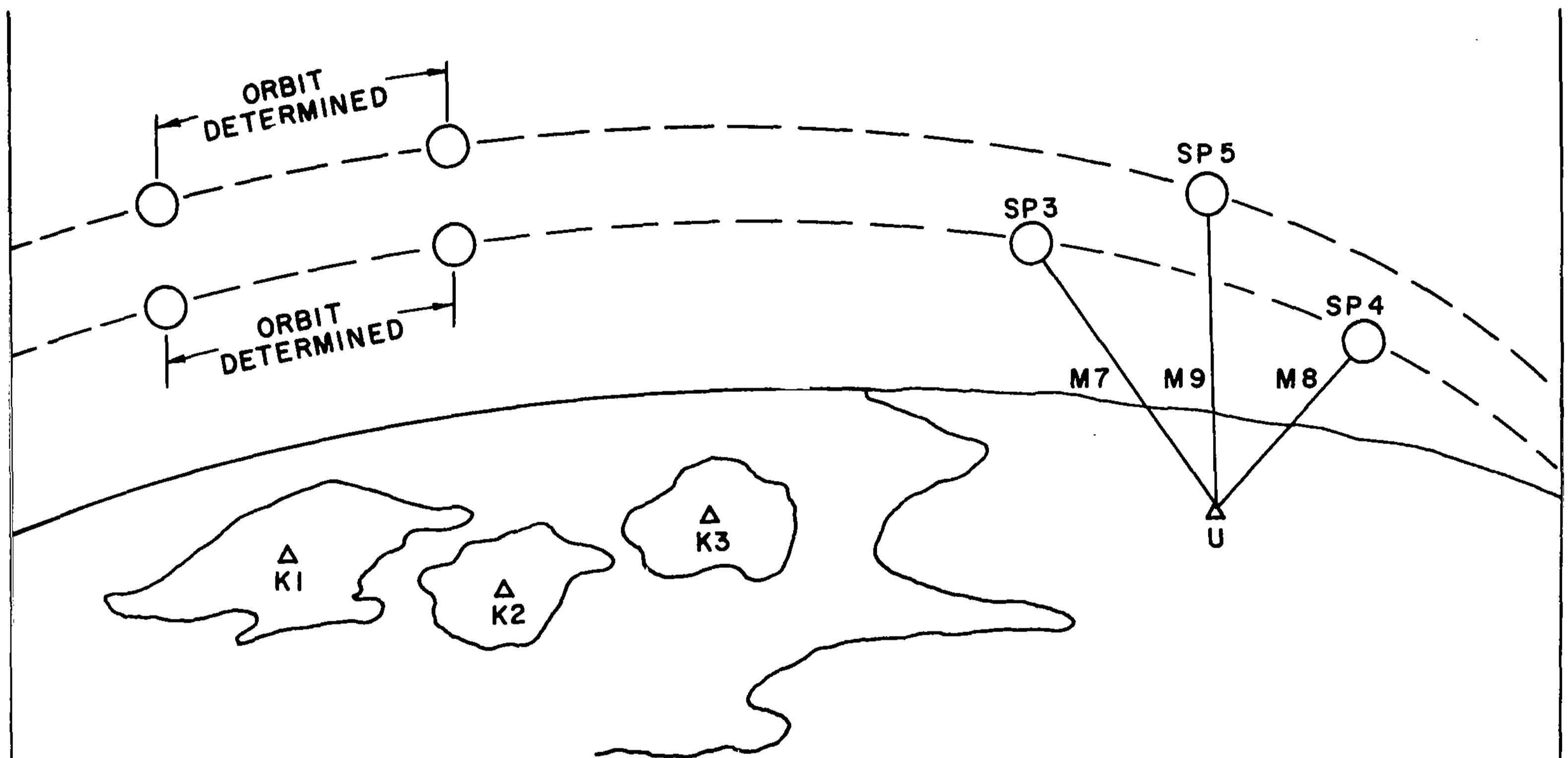
To overcome the geographical limitation and to increase SECOR's flexibility, another method of solution known as the Orbital Mode may be used. In this method, the three known stations observe simultaneously to provide data for a satellite ephemeris, from which the position of the satellite,when observed by the unknown station,is extrapolated. Two or more orbit determinations and at least three distance measurements from the unknown station are required for the simplest geometric solution. Again, many points are determined in practice and an overall station adjustment is used. The Orbital Mode is depicted in Figures 2.2a and 2.2b. This mode has the disadvantage of being dependent on the precise determination of the satellite's orbital parameters, accurate orbit extrapolation, and a very accurate synchronous timing system for all stations.

2.122 Range is determined by SECOR in the following manner. A ground station transmits an electromagnetic wave (carrier) which is phase modulated by known frequency signals. This signal is received and retransmitted by the satellite transponder. The retransmitted signal is at a different carrier frequency to avoid conflict with incoming signals. The ground station then receives this signal which represents the originally transmitted modulated signal with a phase displacement. The phase displacement is measured by an electronic servo and is



The orbit of the satellite is determined by measuring many distances such as M1 thru M6 during the time interval between SP1 and SP2. The position of SP3, at the time M7 is measured, is computed by extending the orbit determined between SP1 and SP2.

Figure 2.2a. Orbit Determination by Orbital Mode.



The positions SP4 and SP5, when measurements M8 and M9 are made, are also computed by extending orbits determined when the satellite was near the known positions. The coordinates of U can then be computed from the distance measurements M7, M8, and M9.

Figure 2.2b. Station Position Determination by Orbital Mode.

linearly proportional to the total distance traveled.

For a given frequency, the range, R, to a satellite can be represented as

$$R = \frac{1}{2}(\Delta\lambda + N\lambda),$$

where

$\Delta\lambda$ = phase displacement of the wave,

λ = wave length of the given frequency,

N = number of full periods of the wave in its total distance traveled.

In the above expression λ is known for a given frequency since

$$\lambda = \frac{C}{f},$$

where C = adopted value of speed of light,

f = known frequency.

Therefore, to measure the range, both the phase shift ($\Delta\lambda$) and the number of periods (N) of the wave must be determined. These factors both depend upon the wave length. To determine N, a long wave length (low frequency) is desirable since it would produce a large non-ambiguous range ($\frac{\lambda}{2}$), from which N could be easily determined by comparing $\frac{\lambda}{2}$ with an approximate orbital range which is usually known. However, a long wave length does not allow a high degree of resolution when measuring the phase shift. For example, if the measuring system can resolve a phase shift to within one degree; we have the following relation:

$$\frac{\Delta R}{1^\circ} = \frac{\lambda}{360^\circ},$$

where ΔR = smallest phase shift measurable (hence, the range measurement error).

Since we want ΔR as small as possible, a short wave length (high frequency) is desirable for resolution.

It is evident then that a single frequency will not be able to provide a high degree of resolution and a large non-ambiguous range.

SECOR overcomes this problem by using four different modulation frequencies, those with shorter wave lengths providing resolution, and longer wave lengths providing maximum non-ambiguous range. The modulation frequencies are generated by a James Knight oscillator with a stability of one part in 10^9 which produces a basic frequency of 1171.065 Kc. Since this one oscillator produces all the modulating frequencies, biases should not occur to the individual channel. The four modulation frequencies are produced by dividing the basic frequency (1171.065 Kc.) by 2, 2^5, 2^9, and 2^{12}, respectively.

A fifth channel, the Extended Range, also contributes to the full range word. The value for the extended range is not obtained from the phase shift, but from the measured round trip transit time of each measuring pulse. This measurement is of low accuracy and is used only as a very rough estimate of the range in resolving ambiguities from the more accurate channels. The following table is a description of the modulating frequencies:

TABLE 1

SECOR MODULATION FREQUENCIES

	Modulation Frequency (Kc.)	Wave Length (meters)	Nonambiguous Range (meters)	System Resolution (meters)
Very Fine	585.533	512	256	0.25
Fine	36.596	8,192	4,096	16
Coarse	2.287	131,072	65,536	256
Very Coarse	.286	1,048,576	524,288	2,048
Extended Range	.020	15,000,000	7,500,000	75,000

The modulation frequencies are used to phase modulate three separate carrier frequencies. The carrier frequency from the ground station is 420.9 Mc. The satellite transmits two carrier frequencies, 449 Mc. and 224.5 Mc., the latter being used only in the calculation of the ionospheric refraction correction to the range. The uplink carrier (to the satellite) and the higher frequency downlink carrier are modulated by all four frequencies while the low frequency (224.5 Mc.) downlink carrier has a single phase modulation frequency (585.533 Kc.)

2.123 An interrogation signal is defined as the carrier wave transmitted from the ground station with its four modulation frequencies. A complete sequence of interrogation signals from the four stations in the network is an interrogation cycle. The cycle is 50 milliseconds long and is divided into a 10 millisecond time zone for each station with a 2.5 millisecond buffer zone in each, thus, each station determines 20 ranges per second.

The sequence of events in an interrogation cycle is as follows. One known station is designated as Master, the other stations as Slave (1,2, and 3). The only difference in the two designations is that the Master station transmits first in the cycle and sends a special timing pulse with its ranging signal to the satellite every 50 milliseconds. The Slave stations interrogate the satellite in their designated sequence and a digital servo at each station keeps a binary representation of the range determined from that interrogation signal. The special timing pulse from the Master station is used to achieve simultaneous range measurements. Upon reaching the satellite, the pulse is retransmitted to all ground stations where it causes the contents of the digital servos to be immediately recorded on magnetic tape. The ranges from all stations then correspond to the time when the timing pulse was at the satellite.

Time is also recorded with each range. Each station has a crystal controlled frequency standard which is checked daily with WWV. These operate time code generators which record UTC time on the magnetic tape each time the digital servos record the range on the tape. The calibration of the frequency standard is corrected for propagation delay time from WWV by adjusting the time code generators.

Since it is imperative that each interrogation signal arrive during its designated 10 millisecond zone, station controls alter the time of signal transmission to account for varying propagation times of the signals. The propagation times vary since all signals travel at essentially the same speed but the range to the satellite is constantly changing.

If the station clocks are not synchronized to 24 milliseconds, the simultaneity of the four ranges can not be verified. Currently, variations in times at the stations seldom exceed a few milliseconds.

2.13 Major Components

A typical ground station layout is shown in Figure 2.3. The ground stations are basically identical and each consists of three air-transportable shelters:

a. The Radio Frequency Shelter contains transmitting and receiving equipment and an antenna control console.

b. The Data Handling Shelter contains data handling and recording equipment which controls the timing and modulation of the transmitted pulses. It also converts the pulses received from the satellite into a form suitable for recording, using both analog and digital techniques.

c. The Storage Shelter contains auxiliary support equipment such as generators, test equipment, and additional antennas.

The shelters are designed for all-weather operation of equipment and are "ruggedized" for ease of handling in

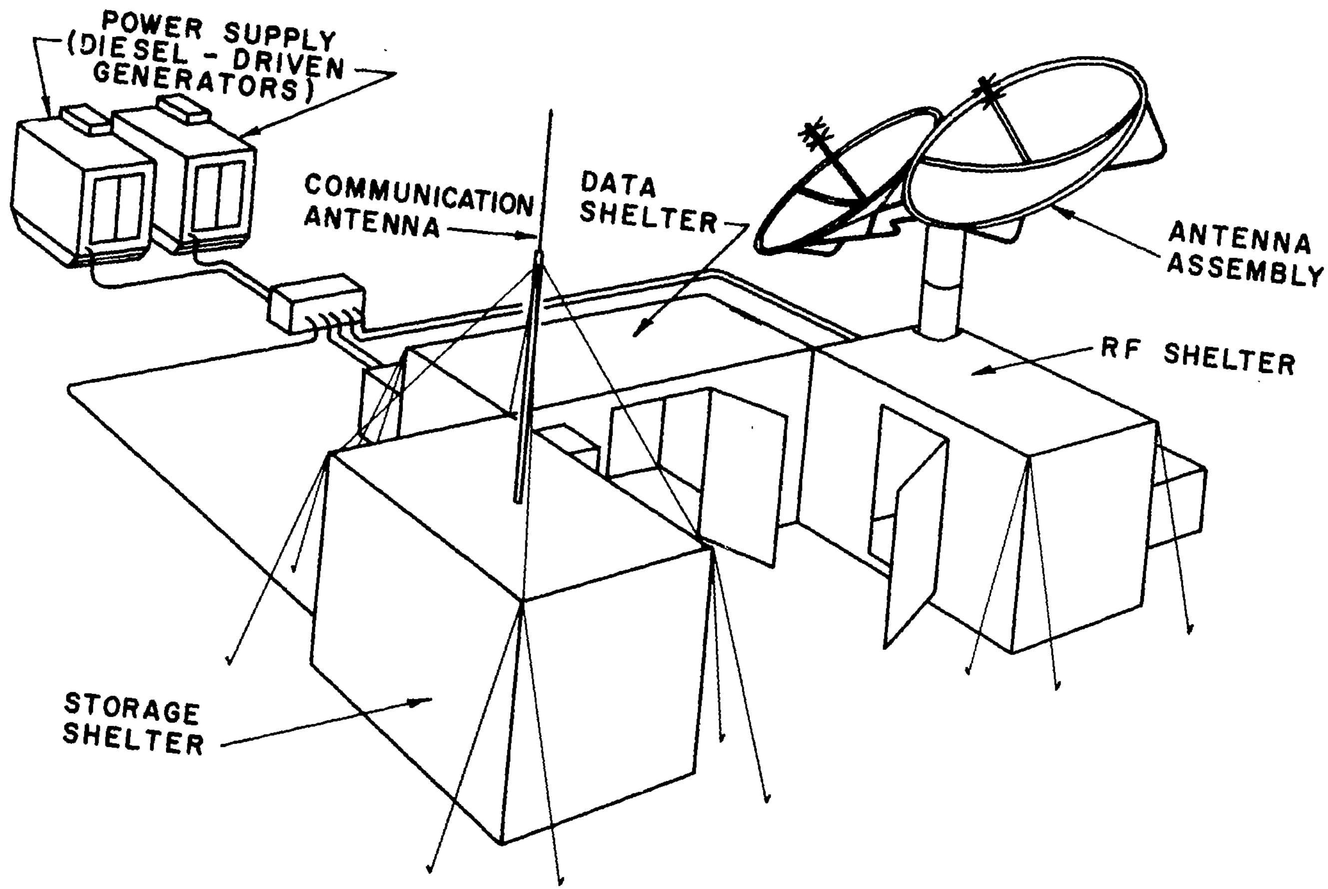


Figure 2.3. SECOR Ground Station Layout.

the field. Once in place, they are connected by an intercom system.

The satellite transponder is basically a remote-controlled radio relay device consisting of a receiver, transmitter, and power supply. It can be mounted in its own satellite or as an integral part of a satellite being used for other purposes. It remains in a stand-by condition until receiving an activating signal from the Master station. The stand-by condition drains minimum power from the batteries, thus prolonging the transponder's operational life.

2.14 Resolution of Range

As previously noted, four wave lengths are used by SECOR to resolve the conflicting requirements of having high resolution plus a large non-ambiguous range. As the modulation frequencies cover too wide a range (see TABLE 1) to be transmitted in that form, they are mixed into the following four signals, suitable for transmission:

D1	585.533 Kc.	(Very Fine)
D2	548.937 Kc.	(Very Fine - Fine)
D3	583.245 Kc.	(Very Fine - Coarse)
D4	549.223 Kc.	(D2 + Very Coarse)

Equipment design resolves the Very Fine channel to a 10-bit digital word which divides the Very Fine wave length into 1024 measurable parts. The other three channels and the Extended Range are expressed as 8-bit words. The five frequencies provide overlapping range measurements from which unambiguous range can be determined.

Figure 2.4 illustrates how the five channels overlap to make up the full range word of 25 bits.

2.15 SECOR Operations

After preliminary testing in the United States in 1963 and 1964, actual tracking operations began in the Pacific in July 1964 and have continued to the present time. The original mission was to provide a tie between the Japanese Datum and the Hawaiian Islands, with a goal of connecting to the North American Datum. Figure 2.5 depicts the network of quads developed as a result of that operation. Present tracking operations continue on a global basis but are generally of a classified nature and are not listed here. A history of all SECOR satellites is given in TABLE 2.

2.2 ARMY MAP SERVICE GEODETIC SATELLITE PROCESSING SYSTEM

2.21 Preprocessing Procedures

The Army Map Service Geodetic Satellite Processing System consists of a series of steps which reduce earth satellite tracking observations in order to develop adjustments to a network of sites. The data sources are Geodetic SECOR range observations.

Figure 2.6 depicts a flow-diagram of the preprocessing portion of the processing system. The following is a

The following illustrates how the five channels overlap to make up the the full range word.

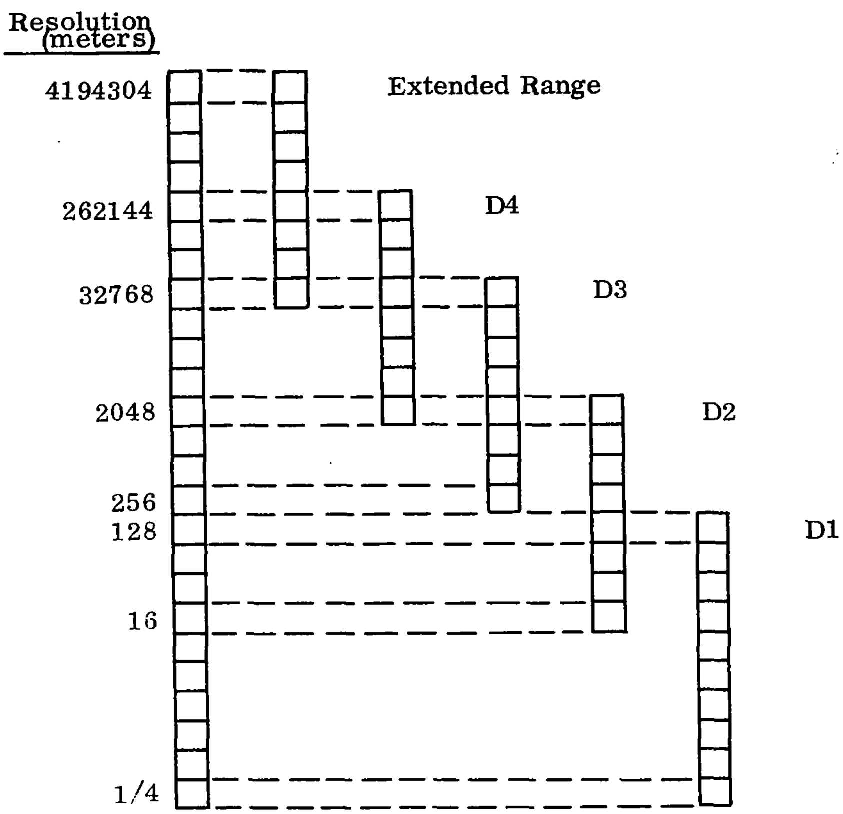


Figure 2.4. Overlap of Ranging Channels.

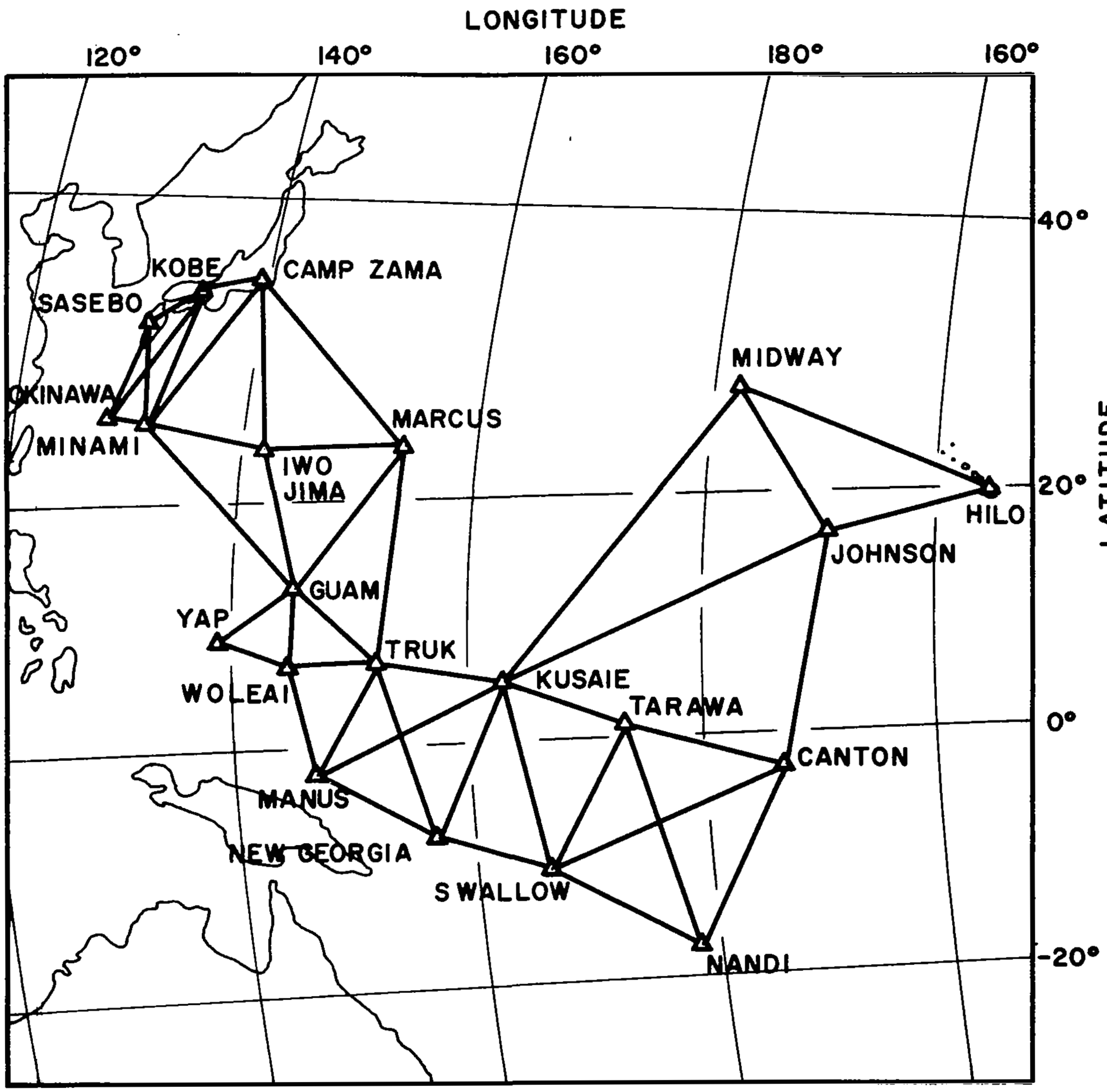
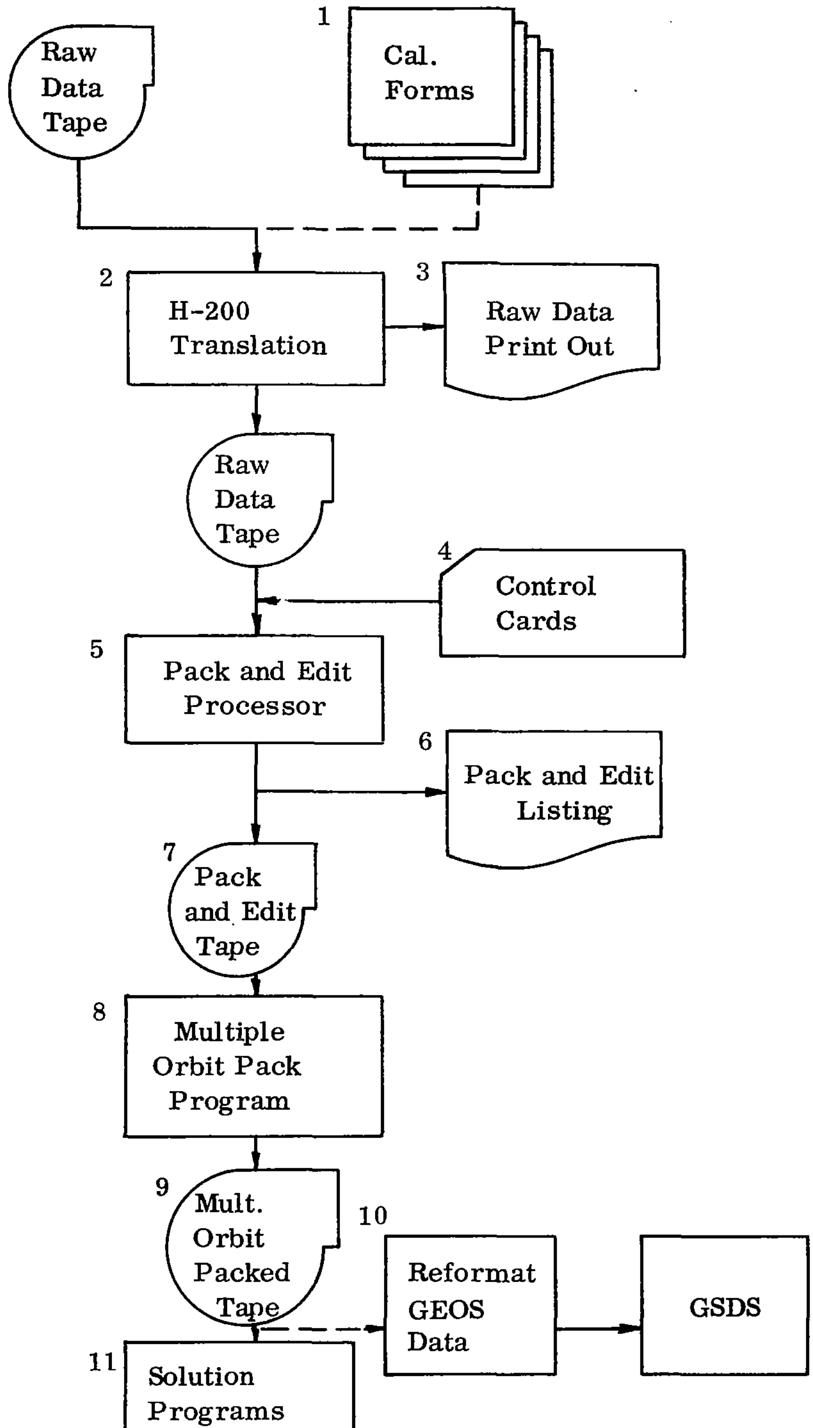


Figure 2.5. SECOR Operational Network.

TABLE 2

SATELLITES WITH SECOR TRANSPONDERS

Satellite Name	International Designation	Inclination (Degrees)	Apogee (km)	Perigee (km)	Date Ceased Functioning
EGRS I	1964-01C	69.9	931	912	Approx. 7-65
EGRS II	Never Operational				
EGRS III	1965-16E	70.0	938	909	
EGRS IV	Never Operational				
EGRS V	1965-63A	69.2	2425	1136	(Used in test only)
EGRS VI	Never Operational				
EGRS VII	1966-77B	90.0	3703	3674	
EGRS VIII	Never Operational				
EGRS IX	1967-65A	89.8	3949	3796	
GEOS A	1965-89A	59.3	2270	1120	Approx. 3-67
GEOS B	1968-02A				



Note: Numbers in figure correspond to numbers of descriptive paragraphs in Section 2.21.

Figure 2.6. AMS Preprocessing Procedures.

description of the flow diagram:

1. During a tracking operation all relevant ranging and timing information is recorded on seven-channel magnetic tape. Data such as pre- and post-calibration settings, meteorological readings (barometer, wet and dry bulb temperature), and station equipment performance are recorded on the following four blank forms:

a) RF Track Evaluation Report
b) Station Pre-Calibration Report
c) Station Post-Calibration Report
d) Calibration Form

At the completion of a track (one pass of the satellite), the magnetic tape and the accompanying forms, where possible, are sent by air mail to Army Map Service (AMS) from each station. The format of the received raw data tape is shown in Figure 2.7.

2. Upon receipt at Army Map Service, the tape is translated by the H200 computer. The original tape is then sent to the Electronic Satellite Tracking Division (ESTD) of AMS for degaussing and reuse by the stations. In the translation the range parts measured on the five channels are put together to form one complete range word (see Section 2.14). The output of the translation process consists of a raw data tape and a raw data listing for preliminary analysis purposes.

3. The Raw Data Listing consists of a print out of every fifth range determination. This is an arbitrary procedure and is done simply for convenience in editing.

Channel Number	Time Word (hr.-min.-sec.-ms.)	Station Constants (qual.-month-sta.-run-day)	Reference Word	D1 Word	D5 Word (ionospheric refrac.corr.)
7	P P P P P P	P P P P P P	P P P P P P	P P P P P P	P P P P P P
6	T M_6 S_6 MS_6	S DA_6	R_6	$D1_6$	$D5_6$
5	H_5 M_5 S_5 MS_5	Q_5 DA_5	R_5	$D1_5$	$D5_5$
4	H_4 M_4 S_4 MS_{10} MS_4	Q_4 MO_4 ST_4 DA_4	R_{10} R_4	$D1_{10}$ $D1_4$	$D5_{10}$ $D5_4$
3	H_3 M_3 S_3 MS_9 MS_3	Q_3 MO_3 ST_3 RU_3 DA_3	R_9 R_3	$D1_9$ $D1_3$	$D5_9$ $D5_3$
2	H_2 M_2 S_2 MS_8 MS_2	Q_2 MO_2 ST_2 RU_2 DA_2	R_8 R_2	$D1_8$ $D1_2$	$D5_8$ $D5_2$
1	H_1 M_1 S_1 MS_7 MS_1	Q_1 MO_1 ST_1 RU_1 DA_1	R_7 R_1	$D1_7$ $D1_1$	$D5_7$ $D5_1$

← Direction of Tape ←

D2 Word	D3 Word	D4 Word	Extended Range	
P P P P P P	P P P P P P	P P P P P P	P P P P P P	P
$D2_6$	$D3_6$	$D4_6$	ER_6	P
$D2_5$	$D3_5$	$D4_5$	ER_5	P
$D2_4$	$D3_4$	$D4_4$	ER_4	P
$D2_3$	$D3_3$	$D4_3$	ER_3	P
$D2_8$ $D2_2$	$D3_8$ $D3_2$	$D4_8$ $D4_2$	ER_8 ER_2	P
$D2_7$ $D2_1$	$D3_7$ $D3_1$	$D4_7$ $D4_1$	ER_7 ER_1	P

Note: Subscript one (1) is least significant bit.
See Section 2.14

Longitudinal Parity Is Last Frame in Each Record

Figure 2.7. Received SECOR Data Tape Format.

Since a determination is made every 50 msec., the time interval between the printed determinations is 250 msec. Figure 2.8 depicts the Raw Data Print Out. Much of the information given in the print out pertains to engineering aspects of the system and is not used in the data analysis.

The following is a description of the columns shown on the Raw Data Print Out:

'Q' Column - This gives an indication of data quality in each servo. A '0' shows that all the electronic servos at the tracking station were locked and that the data should be good. A figure '1' indicates that one or more of the five servos were out of lock and the data are bad (though possibly recoverable).

'T' Column - A '1' is printed out every second (every 20th measurement), otherwise a '0' is shown.

STA - Station number.

RUN - Each run or track recorded during a day is numbered.

DY and MO - Day and month.

E-V, V-C, C-F, F-VF - These columns show the numerical value of the discrepancy between the overlapping parts of the five measuring frequencies that make up the total range word. With the exception of V-C (the overlap between very coarse and coarse) where there are five bits of overlap, four binary bits overlap between the frequencies. In these columns a value of 7 or 8 indicates an

Q	T	STA	RUN	DY	MO	E-V	V-C	C-F	F-VF	ER	VC	C	F	VF	D1-IC	HR	MIN	SEC	TOTAL RANGE	1ST DIF
00000	1	07	1	16	12	+04	+04	+02	+03	4915200	073728	00768	0256	219.50	067.50	04	32	10.050	4784347.50	-0000115
00000	0	07	1	16	12	+03	+04	-02	+01	4882432	071680	64512	3744	153.25	068.00	04	32	10.300	4783769.25	-0000116
00000	0	07	1	16	12	+03	+02	-01	+01	4882432	067584	64256	3168	089.25	068.50	04	32	10.550	4783193.25	-0000116
00000	0	07	1	16	12	+03	+02	+00	+03	4882432	067584	64000	2624	026.50	065.50	04	32	10.801	4782618.50	-0000116
00000	1	07	1	16	12	+04	+02	-01	+01	4915200	065536	62976	2016	216.50	067.00	04	32	11.051	4782040.50	-0000116
00000	0	07	1	16	12	+04	+00	-02	-01	4882432	061440	62208	1408	153.50	066.00	04	32	11.301	4781465.50	-0000115
00000	0	07	1	16	12	+03	+02	-03	+00	4882432	065536	61440	0848	087.75	068.25	04	32	11.551	4780887.75	-0000116
00000	0	07	1	16	12	+03	+06	+02	+05	4882432	073728	62208	0352	027.75	063.25	04	32	11.801	4780315.75	-0000115
00000	1	07	1	16	12	+04	+04	+01	+01	4915200	067584	61184	3808	217.50	068.25	04	32	12.051	4779737.50	-0000116
00000	0	07	1	16	12	+04	+02	+01	+02	4882432	063488	60672	3248	154.75	067.00	04	32	12.301	4779162.75	-0000116
00000	0	07	1	16	12	+04	-01	+01	-01	4882432	057344	60160	2624	091.00	067.25	04	32	12.551	4778587.00	-0000115
00000	0	07	1	16	12	+05	+00	+02	+03	4915200	059392	59904	2112	029.00	065.25	04	32	12.801	4778013.00	-0000114
00000	1	07	1	16	12	+04	-01	+03	+03	4882432	057344	59648	1536	223.50	066.25	04	32	13.051	4777439.50	-0000115
00000	0	07	1	16	12	+05	+02	+02	+03	4915200	061440	58624	0976	161.75	064.50	04	32	13.301	4776865.75	-0000114
00000	0	07	1	16	12	+03	+06	+02	+05	4882432	069632	58112	0432	100.00	064.50	04	32	13.551	4776292.00	-0000114
00000	0	07	1	16	12	+05	+02	+02	+02	4915200	061440	57600	3904	037.75	063.75	04	32	13.801	4775717.75	-0000116
00000	1	07	1	16	12	+04	+02	+02	+03	4882432	059392	57088	3344	232.50	066.00	04	32	14.051	4775144.50	-0000114
00000	0	07	1	16	12	+04	+04	+00	+02	4882432	063488	55808	2752	170.50	066.50	04	32	14.301	4774570.50	-0000116
00000	0	07	1	16	12	+04	-01	-02	-01	4882432	051200	54784	2128	108.50	067.25	04	32	14.551	4773996.50	-0000115
00000	0	07	1	16	12	+05	-01	+00	+00	4915200	051200	54784	1584	049.25	066.00	04	32	14.801	4773425.25	-0000113
00000	1	07	1	16	12	+04	+03	+02	+04	4882432	059392	54784	1072	245.75	065.50	04	32	15.050	4772853.75	-0000115
00000	0	07	1	16	12	+05	+00	+01	+00	4915200	053248	53760	0432	183.00	069.00	04	32	15.300	4772279.00	-0000115
00000	0	07	1	16	12	+05	+02	+00	+01	4915200	055296	52992	3968	123.25	069.25	04	32	15.550	4771707.25	-0000115
00000	0	07	1	16	12	+05	+01	-01	+01	4915200	053248	52224	3408	065.25	065.50	04	32	15.800	4771137.25	-0000114
00000	1	07	1	16	12	+05	-01	+01	-02	4915200	049152	51968	2784	003.25	067.25	04	32	16.050	4770563.25	-0000115
00000	0	07	1	16	12	+04	+02	-01	+00	4882432	053248	50944	2240	200.50	067.00	04	32	16.300	4769992.50	-0000114
00000	0	07	1	16	12	+05	+03	-01	+02	4915200	055296	50432	1696	142.00	067.50	04	32	16.550	4769422.00	-0000114
00000	0	07	1	16	12	+05	+00	-01	-01	4915200	049152	49920	1088	083.75	067.75	04	32	16.800	4768851.75	-0000114
00000	1	07	1	16	12	+04	+03	+02	+04	4882432	055296	50176	0592	026.00	064.75	04	32	17.050	4768282.00	-0000112
00000	0	07	1	16	12	+05	+04	-02	+03	4915200	055296	48640	0000	220.75	066.50	04	32	17.300	4767708.75	-0000115
00000	0	07	1	16	12	+05	+01	-02	+01	4915200	049152	47872	3504	164.25	066.75	04	32	17.550	4767140.25	-0000113
00000	0	07	1	16	12	+04	+00	+02	+03	4882432	047104	48384	2960	106.25	067.25	04	32	17.800	4766570.25	-0000114
00000	1	07	1	16	12	+04	-03	-01	-01	4882432	040960	47104	2320	047.00	067.25	04	32	18.050	4765999.00	-0000114
00000	0	07	1	16	12	+03	+01	+02	+00	4849664	049152	47104	1776	246.50	066.25	04	32	18.300	4765430.50	-0000114
00000	0	07	1	16	12	+04	+02	+01	+01	4882432	049152	46336	1216	188.75	066.50	04	32	18.550	4764860.75	-0000115
00000	0	07	1	16	12	+03	+04	+01	+03	4849664	053248	45824	0688	132.75	064.75	04	32	18.800	4764292.75	-0000114
00000	1	07	1	16	12	+03	-01	+01	+00	4849664	043008	45312	0064	075.75	065.25	04	32	19.050	4763723.75	-0000115
00000	0	07	1	16	12	+04	+02	+00	+01	4882432	047104	44544	3616	018.75	065.00	04	32	19.300	4763154.75	-0000114
00000	0	07	1	16	12	+04	+02	+01	+02	4882432	047104	44032	3056	217.50	066.75	04	32	19.551	4762585.50	-0000114
00000	0	07	1	16	12	+03	+01	+03	+02	4849664	045056	44032	2496	162.75	064.00	04	32	19.801	4762018.75	-0000114
00000	1	07	1	16	12	+03	+02	-01	+02	4849664	045056	42496	1920	106.25	066.00	04	32	20.051	4761450.25	-0000113
00000	0	07	1	16	12	+04	+00	-01	-01	4882432	040960	41984	1312	049.25	066.50	04	32	20.301	4760881.25	-0000114
00000	0	07	1	16	12	+03	-02	+02	-01	4849664	036864	41984	0736	249.50	066.50	04	32	20.551	4760313.50	-0000113
00000	0	07	1	16	12	+04	+01	+02	+00	4882432	043008	41472	0192	195.25	066.50	04	32	20.800	4759747.25	-0000113
00000	1	07	1	16	12	+03	+00	+01	-01	4849664	038912	40704	3696	140.00	065.75	04	32	21.051	4759180.00	-0000112

RMS E-V 01 RMS V-C 02 RMS C-F 01 RMS F-VF 02 STD VF 003.02 STD VFIC 002.64

AV +04 AV +01 AV +00 AV +01 PAGE 0040

Figure 2.8. Raw Data Print Out.

ambiguous meaning. A value of 12 indicates a numerical discrepancy of 4. A major ambiguity in a channel cannot be detected in these columns.

ER, VC, C, F, VF - Ranges in meters are given for the Extended Range, Very Coarse, Coarse, Fine and Very Fine channels.

Dl - IC - Gives the difference in downlink range as measured by the low and high frequency carriers. This is

$$\frac{1}{2}\left(R_{VFIC} - R_{VF}\right).$$

(See par. 2, Sec. 2.222.)

HR MIN SEC - Time when ranging pulse of Master left the satellite. Since every fifth range is printed, this interval between printed times is 250 msec.

Total Range - Range word in meters.

1st DIFF - The first difference to the nearest meter between successive ranges.

The last column of the Raw Data Print Out is manually scanned for a span of five consistent first differences as a starting point for the editing procedures to follow. The first and last times of the span of data to be edited are used as inputs to the editing program.

The above procedure is completed for the tapes from each station tracking a particular pass. For a simultaneous mode solution this is at least four stations, or one quad. However, if stations are already set up on the next interlocking quad, there may be as many as twelve tapes processed for one pass.

4. A card format is then punched for the pass. Its main purpose is to specify the start and stop times for the data at each station. The punched cards and raw data tapes used for the pass are then used as input to the 1108 Computer.

5. The Pack and Edit Processor accepts all the raw data tapes for one tracking mission and performs the following operations:

a) Range data is time-collated and merged to form one tape. This packing process matches data from the stations on a common time base accepting discrepancies of up to 24 msec. Variations greater than this amount would possibly cause a station's data to be included in the wrong interrogation cycle, thus eliminating the simultaneity of the data. This event is very unlikely.

b) As data is processed, ranges are edited only to bring them to the same ambiguity level. This is achieved by comparing the measured 1st difference with the predicted 1st difference, computed from a span of previously edited data using linear extrapolation. The acceptable difference in these two values allows for random noise. The limit for rejecting a sample is twenty meters.

When a discrepancy occurs, multiples of 256 meters are added to, or subtracted from, the new range to bring it within the required tolerance. This is not truly a smoothing process, but only a resolution of ambiguities.

c) A listing of the packed and edited data is produced.

6. The Pack and Edit Listing is used mainly for the resolution of ambiguities. It consists of a print out of every second range determination, this being an arbitrary choice used for economy only. However, the first differences are those between each range determination, not between consecutively printed ones.

The following is a description of the columns shown on the Pack and Edit Listing (see Figure 2.9):

First Time - This is the time chosen during the scan of the Raw Data Print Out. It indicates the beginning of a block of good data.

Master Station - The tape assignment of the master station.

MS TM - The master station time of each range determination at 100 msec. intervals. Only the second and millisecond are printed; hours and minutes being identical to the First Time.

Edited Ranges - The ranges are given in centimeters. The edited ranges differ from the true ranges by the printed edit corrections. Since the Master Station was indicated as tape 4, the fourth column is the Master Station, although

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EDITED RANGE LISTING

FIRST TIME = 7 53 37 500 MASTER STATION= 4

MS TM		EDITED RANGES (CM)				EDIT CORRECTIONS (METERS)				EDITED 1ST DIFF.				D1-IC (CM)			
SC	MS	LARSON	SANDIEGO	WITHIGTO	LYNNLAKE	6	5	7	2	6	5	7	2	6	5	7	2
37	500	151582250	285209050	179928243	145503725	0	9	0	0	130	0	-197	196	3400	9975	1850	3600
37	600	151608375	295422825	179888745	145543025	0	9	0	0	130	0	-197	196	3600	6850	1750	3750
37	700	151634600	305227175	179849294	145582350	0	9	0	0	131	0	-197	196	3775	3750	1675	3750
37	800	151660950	257278050	179809844	145621600	0	9	0	0	131	0	-197	196	3675	2250	1775	3700
37	900	151687325	267081975	179770393	145660975	0	9	0	0	132	0	-197	197	3475	2325	1850	3750
38	0	151713700	277705650	179731093	145700325	0	9	0	0	132	0	-196	196	3400	2000	1825	3700
38	100	151740125	294063575	179691745	145739700	16384	9	516352	0	132	0	-196	196	3250	2000	1750	3775
38	200	151766625	304687150	179652394	145779050	16384	9	504064	0	132	0	-196	196	3150	2075	1775	3750
38	300	151793175	308757025	179613018	145818500	16384	9	483584	0	132	0	-196	196	2950	2800	1900	3800
38	400	151819800	266131925	179573795	145857925	0	9	0	0	133	0	-195	197	2725	3325	1825	3850
38	500	151846450	277165400	179534543	145897400	0	9	0	0	133	0	-196	197	2625	2650	1750	3800
38	600	151873100	287379675	179495244	145936875	0	9	0	0	133	0	-196	197	2625	2550	1875	3875
38	700	151899700	291449450	179456044	145976325	0	9	0	0	133	0	-196	197	2425	2775	1850	3850
38	800	151926275	302073300	179416844	146015875	0	9	0	0	132	0	-195	197	2625	2025	1750	3825
38	900	151952800	259858425	179377695	146055400	0	9	0	0	132	0	-195	198	2550	2400	1775	3775
39	0	151979350	264338525	179338545	146095025	16384	9	512256	0	132	0	-195	198	2900	2325	1850	3775
39	100	152006000	274552375	179299444	146134575	16384	9	504064	0	133	0	-195	198	3100	2575	1875	3850
39	200	152032700	285175900	179260394	146174175	16384	9	491776	0	133	0	-195	198	3225	2775	1700	3900
39	300	152059350	289655925	179221293	146213825	0	9	0	0	133	0	-195	198	3375	2375	1750	3900
39	400	152086050	299895300	179182195	146253450	0	9	0	0	133	0	-195	197	3175	2550	1875	3950
39	500	152112800	304349675	179143094	146293100	0	9	0	0	133	0	-195	198	3175	2300	1875	3900
39	600	152139600	262953925	179104120	146332775	0	9	0	0	134	0	-194	198	3050	2650	1800	3950
39	700	152166500	266614400	179065169	146372525	0	9	0	0	134	0	-194	198	2925	2625	1800	3800
39	800	152193500	277647900	179026193	146412200	0	9	0	0	135	0	-194	198	2750	2475	1825	3825
39	900	152220425	282127750	178987219	146451975	16384	9	499968	0	135	0	-195	199	2675	2400	1875	3875
40	0	152247400	292342075	178948345	146491700	16384	9	528640	0	135	0	-193	198	2675	2425	1875	3900
40	100	152274325	303401275	178909469	146531500	16384	9	491776	0	134	0	-194	199	2600	2150	1850	3875
40	200	152301100	307881175	178870595	146571275	0	9	0	0	134	0	-193	199	3000	2000	1775	3850
40	300	152327950	265666625	178831720	146611125	0	9	0	0	134	0	-194	199	2975	1925	1800	3775
40	400	152354850	270120600	178792894	146650875	0	9	0	0	134	0	-193	198	3100	1925	1750	3925
40	500	152381850	274190725	178754094	146690775	0	9	0	0	135	0	-193	199	2950	2050	1725	3850
40	600	152408900	284814750	178715345	146730650	0	9	0	0	135	0	-193	199	2900	2025	1725	3900
40	700	152435950	289294425	178676620	146770550	0	9	0	0	135	0	-193	199	2850	2225	1750	3975
40	800	152463025	299918400	178637895	146810450	16384	9	512256	0	135	0	-193	199	2875	2150	1700	3975
40	900	152489975	303988975	178599144	146850325	16384	9	504064	0	135	0	-193	199	2925	1825	1725	3875
41	0	152517025	308878550	178560519	146890325	16384	9	499968	0	135	0	-193	200	3125	1800	1775	3925
41	100	152544225	266664125	178521819	146930300	0	9	0	0	136	0	-193	200	3150	1700	1800	3825
41	200	152571350	271118600	178483144	146970275	0	9	0	0	135	0	-193	199	3375	1675	1875	3950
41	300	152598575	281742650	178444569	147010275	0	9	0	0	136	0	-193	199	3350	1675	1750	4050
41	400	152625875	292392500	178405969	147050325	0	9	0	0	136	0	-192	200	3050	1425	1825	3925
41	500	152653200	303426025	178367394	147090375	0	9	0	0	136	0	-193	200	2925	1525	1875	3775
41	600	152680475	261647175	178328844	147130425	0	9	0	0	136	0	-192	200	2825	1250	1950	3900
41	700	152707700	265717650	178290344	147170550	16384	9	495872	0	136	0	-192	200	2675	1175	1975	3975
41	800	152734975	270197675	178251844	147210700	16384	9	495872	0	136	0	-192	201	2800	1125	1900	3900
41	900	152762325	274652325	178213319	147250775	16384	9	499968	0	136	0	-192	200	3075	1000	1900	3850

Figure 2.9. Pack and Edit Listing.

its station number is 2.

Edit Corrections - The printed correction is the ambiguity (multiple of 256) which was added to or subtracted from the range to get the edited range in consonance with the previous edited ranges. A "9" printed in one of the columns indicates that the measured range differed from the predicted range by more than the ambiguity (256 m) plus the noise level (20 m) and therefore was not edited.

Edited 1st DIFF - The 1st differences are in meters and are those between each range determination, even though only every 2nd determination is printed.

D1 - IC (CM) - This is the difference, in centimeters, between the ranges measured on the low and high frequency carriers.

7. All usable data relating to a single track are now concentrated in convenient and economical form on the pack and edit tape for storage and computations. After a number of pack and edit tapes are available, they are used as input to the Multiple Orbit Pack Program. The individual pack and edit tapes are then reused.

8. The Multiple Orbit Pack Program combines the individual pack and edit tapes onto one Multiple Orbit Packed Tape. The number of passes on the tape depends upon the length of each tracking operation.

9. The Multiple Orbit Packed Tape contains all

the data, in the same format, which was on each pack and edit tape. This procedure is used for economy of storage only. The Multiple Orbit Packed Tapes are then permanently stored at Army Map Service and are used as input to the Simultaneous Mode or Orbital Mode Solutions.

10. Data obtained from GEOS A and GEOS B satellites only is reformatted into the required GSDS format (see APPENDIX A), then submitted to the Geodetic Satellites Data Service.

11. The primary function of the solution programs is to determine the coordinates of the unknown station in the quad. Since this is beyond the preprocessing procedures, the two methods of solution are only mentioned briefly.

a. Simultaneous Mode - This method of solution is mentioned in Section 2.121. In this mode, the three known stations are considered to fix an errorless satellite position. This allows for adjustment of the coordinates of the unknown station only.

b. Orbital Mode - This is currently the primary method of solution, also described in Section 2.121. In this method, preliminary orbits are fit to the observation data using a least squares technique. The fitting procedure assumes a fixed epoch. All corrections are computed and applied and the orbit is constrained, allowing for an overall adjustment of station coordinates.

2.22 Corrections to Data

2.221 The following corrections are applied to SECOR data during preprocessing:

1. Propagation delay from WWV

This correction is applied at the tracking station by adjusting the time code generators, no mathematical correction is applied to data.

2. Ambiguity Correction

This correction is applied during the Pack and Edit Program by comparing measured and predicted 1st differences. The ambiguity which was added to, or subtracted from, the measured range is printed on the Pack and Edit Listing. It should be remembered that this correction only brings all ranges to the same ambiguity level and does not necessarily remove any constant ambiguity remaining in all the data.

2.222 The following corrections remain to be applied to SECOR data stored at AMS. The numerical corrections listed are those applied by AMS in their programs solving for station coordinates.

1. Calibration Correction

This correction is determined by calibrating the tracking equipment at the station before and after tracking. Data for computing the correction is obtained from the calibration forms sent from the tracking stations. The corrections are computed for both the VF (449 Mc.) and VFIC (224.5 Mc.) channels.

a. The correction for the VF channel is

$$\text{Cal. VF} = \frac{\text{Pre-Cal. VF} + \text{Post-Cal. VF}}{2} - \text{SAT. DELAY VF},$$

where

Cal. VF = total calibration correction to the VF (449 Mc.) channel,

Pre-Cal. VF = pre-track calibration value (obtained from forms sent by stations),

SAT. DELAY VF = satellite transponder delay on the VF channel.

The satellite transponder delay is considered constant for a particular satellite. The values of the delay are sent to AMS from the ESTD at Herndon, Virginia. The equipment is adjusted prior to the track so that the pre-calibration values and post-calibration values on both channels are normally close to zero.

The calibration correction on the VF channel is added to the measured range in order to remove any zero set error.

b. The correction for the VFIC channel is

$$\text{Cal. VFIC} = \frac{\text{Pre-Cal. VFIC} + \text{Post-Cal. VFIC}}{2} - \text{SAT. DELAY VFIC},$$

where

Cal. VFIC = total calibration correction to the VFIC (224.5 Mc.) channel.

Other terms are defined as for the previous calibration correction except all are measured on the VFIC channel. Both the VF calibration correction and the VFIC calibration correction are utilized in the computation of the ionospheric refraction correction.

2. Ionospheric Refraction Correction

SECOR used carrier signals which are of sufficiently high frequency to penetrate the ionosphere, however the signal is retarded slightly in the process. For an elevation angle greater than 10°, ionospheric bending of the electromagnetic wave causes no significant range error [Prescott, 1965]. However, the velocity difference, or retardation, of the wave can cause errors of 5 to 100 meters. The amount of retardation, to a first approximation, varies inversely as the square of the frequency. SECOR uses the difference between ranges measured on the low and high frequency carriers from the satellite to compute a correction for retardation due to the ionosphere. Theoretically, the higher frequency channel measures a shorter range. As shown in Section 2.12, the three carrier frequencies involved are:

f_1 = 420.9 Mc. = carrier from ground station
f_2 = 449 Mc. = high frequency satellite carrier
f_3 = 224.5 Mc. = low frequency satellite carrier

By using the above relationship, we can say that

$$\Delta R = K[(D1 - IC) - CAL._{VF} + CAL._{VFIC}],$$

where

ΔR = range correction due to ionospheric refraction, which is added algebraically to the measured range,

$$K = \frac{f_1^{-2}+f_2^{-2}}{f_2^{-2}-f_3^{-2}} = -.7125,$$

(D1 - IC) = one half of the range measured on the VFIC channel minus the range measured on the VF channel $\left(\frac{R_{VFIC} - R_{VF}}{2}\right)$. This is recorded in the 10-bit D5 data word on the raw data tape. The D1 terminology is used probably since the VFIC carrier is modulated only by the D1 frequency (see Section 2.14).

In the event that high noise content in the (D1 - IC) channel renders the dual frequency correction technique impractical, the following model is used for the ionospheric refraction correction:

$$\Delta R = \frac{40.3}{f^2} S(\Phi) F(X,R)\ H \frac{\left[\tan^{-1}\left(\frac{Z_s - Z_m}{H}\right) + \tan^{-1}\left(\frac{Z_m}{H}\right)\right]}{\left[1 - \frac{\cos^2 E}{\left(1 + \frac{Z_m}{P}\right)^2}\right]^{1/2}},$$

where

ΔR = range correction (meters),
Z_s = satellite height (meters),
Z_m = height of maximum electron density (meters),
H = scale height (meters),
P = mean earth radius (meters),
E = elevation angle of satellite,
f = carrier frequency,
$F(X,R)$ = function of sun's zenith angle effects on ionosphere,
$S(\Phi)$ = function of earth's magnetic field,
X = sun's effective zenith angle,
Φ = effective magnetic latitude,
R = parameter dependent on satellite height [Cubic Corp., 1967].

The modeled ionospheric refraction correction is subtracted from the measured range.

3. Tropospheric Refraction Correction

The following empirical formula is used which is accurate to within 10% of the correction:

$$\Delta R = \frac{K_1(1-e^{-ZR})}{\text{SIN } E_o + K_2 \text{ COS} E_o}, \qquad \text{[Prescott, 1965]}$$

where

ΔR = correction in meters,
K_1 = zenith refraction value = 2.7 meters,
K_2 = control constant = .0236,
Z = control constant = $\frac{1}{7000}$ meters,
R = slant range (meters),
E_o = elevation angle.

This correction is subtracted from the measured range.

4. Ambiguity Correction

As mentioned in Section 2.221, there can be a constant ambiguity remaining in the data stored on the Multiple Orbit Packed Tape. To remove this ambiguity, a trial and error type procedure is used.

A calculated estimate of the ambiguity is made initially by examining the printed edit corrections on the Pack and Edit Listing. These are compared with the predicted range based on NASA estimates which are published covering a two-week period. The estimate of the ambiguity is then added to the edited range and the solution program is run to obtain the station coordinates. The computed coordinates are compared with known approximate coordinates. If there is an obvious discrepancy, another estimate of the ambiguity is made and the process is repeated.

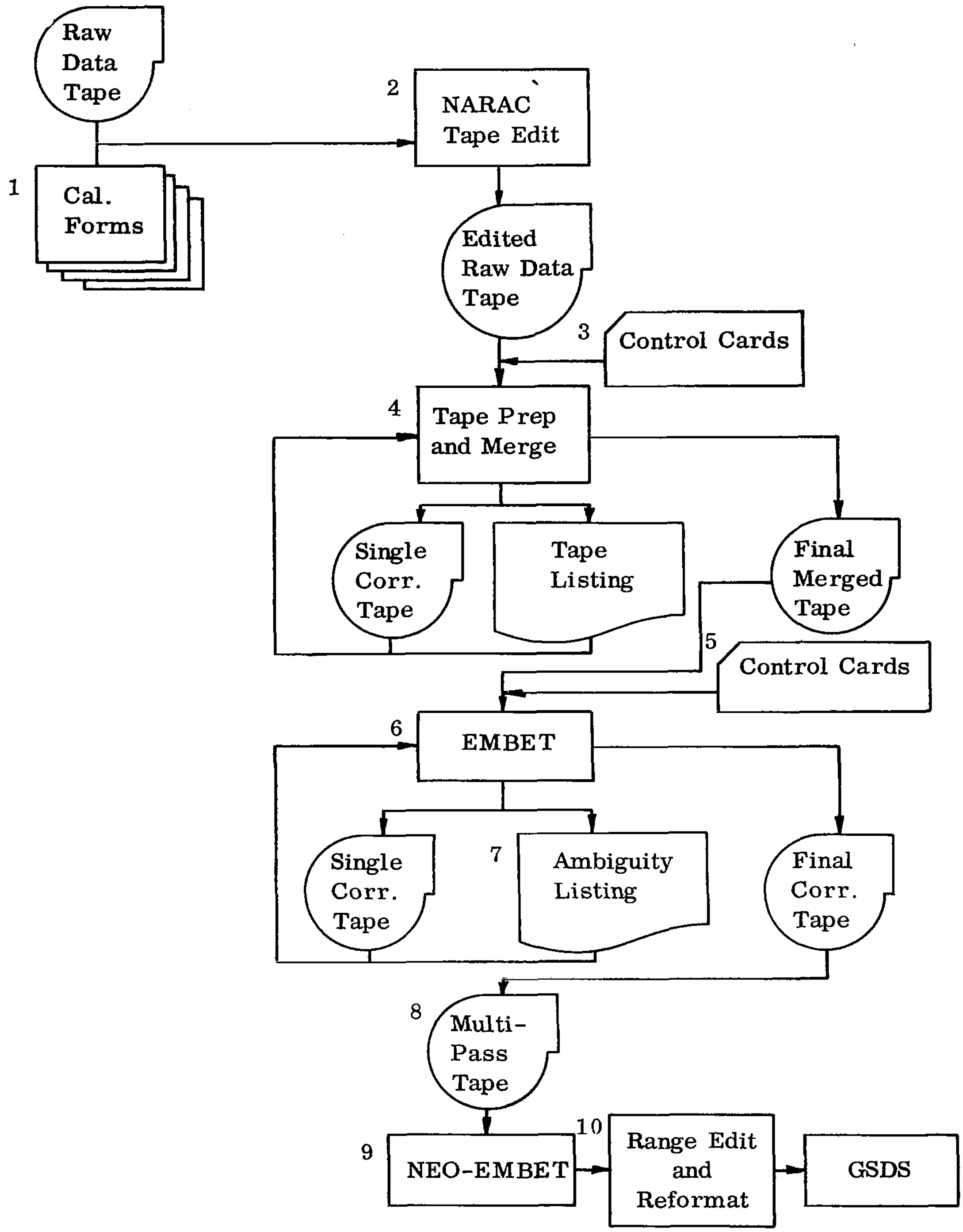
Discrepancies in the solution are determined by examining the range residuals on the output of the solution program. The residuals from the simultaneous solutions are computed by treating each of the four stations as unknown in turn, solving for its range, and comparing this computed range with the observed range from that station. An ambiguity will show up as an unusually large residual. The most frequently occurring ambiguities are those equal to the half-wave-lengths of the modulating frequencies (see TABLE 1).

2.3 U.S. ARMY ETL SECOR DATA PROCESSING SYTEM

2.31 Preprocessing Procedures

The U.S. Army Engineer Topographic Laboratory SECOR Data Processing System was developed under contract by D. Brown Associates for the reduction of data from the Geodetic SECOR System. All SECOR data in the Geodetic Satellites Data Service (GSDS) until 1 February 1968 was processed by this method. However, it is not any longer used to process data for the GSDS. (See Section 2.4 for explanation.) Figure 2.10 depicts a flow diagram of the preprocessing procedures applied to data submitted to the GSDS by ETL. The following is a description of the flow diagram:

1. Initial input to the process consists of a copy of the raw data tape from Army Map Service. Figure



Note: Numbers in figure correspond to numbers of descriptive paragraphs in Section 2.31.

Figure 2.10. ETL Preprocessing Procedures.

2.7 is an illustration of the format of the raw data tape. ETL also receives copies of the calibration forms forwarded from the tracking station to AMS.

2. The raw data tape, containing data from one station, is run through an editing program on a NARAC computer. This program removes any end-of-file marks which are imbedded in the data and also any spikes resulting from the initial power surge of the tracking equipment. The program also increases the density of the data from the received 200 bits/inch to 556 bits/inch, which is compatible for input to the CDC 3800 computer.

3. The output tape from the NARAC program contains all original data without the extraneous clutter mentioned above. This tape, along with three control cards, is input to the next program. The control cards contain the following information:

a) Orbit number, date of track, date of processing, start and stop times of track,

b) Orbit number, data point interval, 2 calibration corrections, merge option,

The interval between data points is usually selected as one range/sec., which means only one in twenty data points is used by the program. The two calibration corrections are denoted by AIC and BIC. One, AIC, is applied to the range, while both are used in computing the ionospheric refraction correction (see Sec. 2.32). These corrections are dependent on the ground station which recorded the tape, and are manually calculated from data on the calibration forms from that station.

c) Print options.

4. The tape is used as input to the Tape Prep and Merge Program on the CDC 3800 computer. In this program the range parts measured on the five channels are put together to form one complete range word (see Section 2.14). The program also computes a correction for zero set error and for ionospheric refraction and applies the corrections to the data. The ionospheric refraction correction is applied only when both AIC and BIC values are given as input and when good data is available from the (D1-IC) (D5) channel, otherwise, it is modeled later in the process. Section 2.32 gives a description of the corrections. If the range word is garbled due to excessive noise, no corrections are applied and that data point is deleted.

Program output consists of the following:

a) A tape containing original data for one station with zero set and ionospheric refraction corrections applied,

b) A list of corrected data for one station,

c) A tape containing merged, corrected (ionospheric refraction and zero set) data from all stations which tracked on a particular pass. Ambiguities are still present in the data at this point. The data points on this tape are at one second intervals. This tape is recorded as follows: the corrected tape from one station in 4a is obtained and then used as input to the same program along with an uncorrected tape and control cards from another station which tracked on the same pass. Output from this cycle consists of that listed in 4a and 4b for the new station only, and the merged tape containing corrected data from both stations. This process is repeated for each station (from four to twelve) which tracked on the pass, always using the previously corrected tapes, uncorrected tape from a particular station, and control cards for the uncorrected tape as input.

5. The above process results in a final merged tape containing all corrected data for one pass with observation times in chronological order. This tape is used as input to the EMBET Program. Also used as input are control cards containing the following:

a) Run type options, data point interval, start and stop times.

b) Geodetic coordinates of observing stations. Latitude and longitude are given in degrees, minutes, seconds, and elevation is in meters.

c) Estimate of the standard deviation of the observations, stated in terms of one sigma values (rather than 3 sigma), one for each observation channel.

d) Estimate of orbital elements and their standard errors. These estimates are obtained from orbit prediction tables published by NASA.

e) Elevation angle (degrees) below which all data taken will be ignored (usually ten degrees), and ground level index of tropospheric refraction.

f) Values for various physical constants:

Earth's semi-major axis	-	6378206.4 meters
Earth's eccentricity squared	-	.0067686580
Geocentric Gravitational Constant	-	3.9860300×10^{14} m^3/sec^2
Sidereal Rotation Rate of Earth	-	7.2921150×10^{-5} rad/sec.
Conventional Zonal Harmonic Coefficients	-	J2: 1.08268×10^{-3} J3: -2.59×10^{-6} J4: -1.53×10^{-6} J5: 0.0 J6: 0.0 J7: 0.0

Note that items ignored include: tesseral harmonics, atmospheric drag, radiation pressure, and Luni-solar perturbations.

6. The Error Model Best Estimate of Trajectory (EMBET) Program determines the orbital elements of a satellite as a means for removing ambiguities in the data. It accomplishes this through a Least Squares Adjustment using the method of Variation of Parameters. The mathematical structure for this adjustment is

$$R_{ij} = \left[(X_j-X_i)^2 + (Y_j-Y_i)^2 + (Z_j-Z_i)^2\right]^{1/2},$$

where

R_{ij} = range from station to satellite,

X_j, Y_j, Z_j = coordinates of satellite,

X_i, Y_i, Z_i = coordinates of tracking station.

The initial approximations for the coordinates are obtained from the control cards.

The true range to the satellite can also be represented as

$$\underset{\text{(Adjusted Range)}}{\overset{a}{R_{ij}}} = \underset{\text{(Observed Range)}}{\overset{o}{R_{ij}}} + \underset{\text{(Systematic Error)}}{R_{ij}} + \underset{\text{(Random Residual)}}{V_{ij}} .$$

The procedure for a least squares adjustment of these parameters is widely known and will not be restated here [Brown, 1966].

The entire process is repeated using the results of the first adjustment as approximations to the next iteration. This continues until convergence occurs, or until a pre-set number of iterations, (currently four) take place without convergence. In the latter case, the data is withdrawn and examined for possible reuse with different estimates of the orbital elements.

The EMBET Program also computes and applies the tropospheric refraction correction, and models the ionospheric refraction correction when necessary. The elevation angle is computed and if less than the value on the control card, the data point is deleted. Section 2.32 lists these corrections in detail.

7. The output listing of this program consists of the range residuals in meters and is manually scanned for ambiguities. Once determined, control cards are punched containing the amount of ambiguity to be removed and the entire EMBET Program is repeated using the original input, with the additional control cards.

The output listing of the second run is scanned for remaining ambiguities and, if present, the process is repeated until none remain.

The final output tape from this program contains data from one pass which has been corrected for all known systematic errors. It is possible however for some undetermined systematic error to remain in the data.

8. The tape is then merged with corrected tapes from other passes. This is used as input to the NEO-EMBET Program. Control cards, which are essentially a consolidation of those used in step 5, are also used as program input.

9. The N-Epochal Orbital EMBET (NEO-EMBET) Program is run on the CDC 3800 Computer. Its main purpose is to remove any systematic error remaining in the data. This is accomplished by the simultaneous reduction of all passes over a given quad, since the systematic errors from each pass can be considered random over a number of passes. For each pass, a new set of orbital elements and coefficients for the systematic error model are determined. The adjusted

quantities are the coordinates of a preset number of the tracking stations in the net, the remaining stations' coordinates being fixed. (For additional information see Brown, 1966.)

10. After the multi-pass adjustment of NEO-EMBET, the resulting orbital elements are constrained, and a range is computed for each station at one second intervals. A range residual (computed - observed) is computed for each point, then all data points with residuals having absolute values greater than 50 m are deleted.

Data points whose residuals fall within the acceptable limits are immediately reformatted on tape into that format required by the GSDS (see APPENDIX A).

2.32 Corrections to Data

2.321 The following corrections are applied to SECOR data during preprocessing at ETL:

1. Zero Set Correction

The zero set correction is determined by calibrating the tracking equipment at the station before and after tracking. Data for computing the correction is obtained from calibration forms sent from the tracking stations. The correction is manually computed, then used as input to the Tape Prep and Merge Program, as follows:

AIC = A + STA. TCU VF - SAT. ANT. DELAY VF,

where

AIC = total calibration correction to the VF channel,

$$A = \frac{\text{Pre-Cal.VF + Post-Cal.VF}}{2}$$

(One half the sum of the pre-track calibraion and the post track calibration on the VF channel),

STA. TCU. VF = station calibration delay on VF channel as determined by a Transponder Calibration Unit (this is used by AMS only as a check in their current processing),

SAT. ANT. DELAY VF = satellite transponder dealy + station antenna delay, on the VF channel.

The satellite transponder delay is considered constant for a particular satellite. The station antenna delay correction is no longer used by AMS. The zero set correction is added to the measured range.

2. Ionospheric Refraction Correction

If acceptable (low noise level) data is available on the (D1-IC) channel the following ionospheric refraction correction is computed and applied in the Tape Prep and Merge Program:

$$\text{IC corr.} = -.7125\ [(\text{D1-IC}) + \text{BIC} - \text{AIC}],$$

where

-.7125 = frequency ratio described in Section 2.222,

(D1 - IC) = difference in ranges determined from the two satellite carrier frequencies (VFIC - VF), which is recorded as data word D5,

AIC = zero set correction previously computed,

BIC = B + STA. TCU VFIC - SAT. ANT. DELAY VFIC. (Total calibration correction to the VFIC (224.5 Mc.) channel. Other terms are defined as for the AIC correction except all are measured on the VFIC channel. This correction is manually computed then used as input to the Tape Prep and Merge Program.)

If the two-frequency data are not available, the ionospheric refraction correction is modeled in the EMBET Program as follows [Brown, 1966]:

$$\text{IC corr.} = -2(\text{COS } Z_i + \sqrt{\text{COS}^2 Z_i + B_2 \text{ SIN}^2 Z_i})^{-1},$$

where

$B_2 = 416667\ (R + 200000)^{-1}$
(R is the measured range with corrections applied for zero set error and ambiguities),

$\text{SIN}^2 Z_i = (1 - \text{SIN}^2 E) R^2 (R + 200000)^{-2}$,

E = local elevation angle of ray upon entry to ionosphere.

E is computed from

$$\text{COS } E = (r_o \text{ COS } E')\ (r_o + h_m - 3H)^{-1},$$

where

r_o = geocentric distance of observer,

E' = apparent elevation angle at observer,

h = altitude of layer of maximum electron density in ionosphere,

H = scale height of ionosphere (50 km),

$\therefore$ $(h_m - 3H)$ represents the height of the base of the ionosphere,

$\text{COS}^2 Z_i = 1 - \text{SIN}^2 Z_i$.

The ionospheric refraction correction is added algebraically to the measured range.

3. Tropospheric Refraction Correction

This correction is computed and applied in the EMBET Program as follows [Brown, 1966]:

$$\text{Tropo. Corr.} = -\alpha\left[\text{SIN } E + (\text{SIN}^2 E + 1^2)^{\frac{1}{2}}\right]^{-1},$$

where

$\alpha = 2(n_o - 1)H_o$,

n_o = index of refraction at observer (obtained from control cards),

H_o = 7200 meters (upper limit of troposphere),

E = elevation angle of satellite, computed as before,

$1^2 = 4H_o r_o^{-1}$,

r_o = geocentric distance of observer.

4. Propagation Delay from WWV

This correction is applied at the station.

2.322 The following corrections remain to be applied to SECOR data:

All data from GEODETIC SECOR in the GSDS as of February 1, 1968 (23 orbital passes) was processed by the USAETL Satellite Data Processing System just described. However, if the two-frequency data was not available, no ionospheric refraction correction was applied. Due to some other problems with the data, it should not be used until it is reprocessed (see Section 2.4).

2.4 DISCUSSION

As of 1 February 1968, no data has been submitted by Army Map Service to the Geodetic Satellites Data Service at Greenbelt, Maryland. The primary reason for this is that the AMS data is not in the format required by GSDS. Current plans at AMS call for the development of a program which will reformat the Multiple Orbit Packed Tapes into the GSDS format. Once the program is obtained, all AMS data from GEOS A and GEOS B satellites will be reformatted and submitted to GSDS. In the reformat program, all corrections will be incorporated as part of the preprocessing. Data obtained by AMS from other satellites will not be reformatted. Plans call for SECOR data to be submitted with a density of 1 observation per 4 seconds. Data will be submitted with the ionospheric refraction correction given in columns 71-76, not the value of (D1-IC) as specified in the format.

By 1 March 1968, data from approximately 100 passes will be submitted to the GSDS. Plans call for data from approximately 250 passes to be in the GSDS by 1 May 1968.

Since no data smoothing procedure is used during preprocessing at AMS, all usable data points are recoverable from the Multiple Orbit Packed Tape. The only data which is lost, is that screened out as unusable during the manual edit of the Raw Data Print Out (Sec. 2.22, par. 3). The percentage of data which is edited as unusable is completely variable, depending on the conditions present during each pass.

The unusable data is primarily caused by

a. A tracking station in the quad not in a phase-locked condition,

b. The tracking elevation angle is less than 10 degrees.

Although Figure 2.10 indicates that the SECOR data processed by Engineer Topographic Laboratories is submitted to the GSDS, this is not currently being done. All SECOR data in the GSDS as of 1 February 1968 was processed by USAETL, however this was due to a specific project and the data is from 23 orbital passes of GEOS A only.

Due to some questions arising regarding the appropriateness of certain corrections applied to this data, and the proper synchronization of the station clocks, it is planned to withdraw it from the GSDS for additional analysis and reprocessing. It is recommendea that the SECOR data in the data center prior to 1 February 1968, processed by ETL, should not be used for geodetic purposes until further analysis of that data will be possible.

3. GODDARD RANGE AND RANGE RATE SYSTEM

3.1 GENERAL SYSTEM DESCRIPTION

3.11 Introduction

An electronic satellite tracking system capable of geodetic accuracy currently being operated by the National Aeronautics and Space Administration is the Goddard Range and Range Rate System (GRARR). As the name implies, this system is capable of determining both the range and the rate of change of the range to a satellite. The range is measured by determining the phase shift between ground-transmitted sidetones and satellite transponder returned sidetones. This phase shift is proportional to the total distance traveled. The range rate is determined from the two-way Doppler shift of the uplink carrier frequency (station to satellite). The Doppler shift of the signal is due to the satellite motion relative to the tracking station. The position of the satellite can theoretically be determined by one observation at one known station since the system output also gives the X- and Y- angles of the antennas (see APPENDIX B). Two generations of equipment, with slightly different characteristics, are currently in use. These will be designated GRR-1 and GRR-2. Section

3.15 gives a general description of the system differences.

3.12 Principles of Operation

The GRARR System has an auto-tracking capability and utilizes uplink carrier frequencies of both VHF and S-Band. In current operation, the VHF channel with its relatively broad beam (about 18°) is used initially to acquire the satellite by detecting its transmitted VHF signal. During the acquisition function, the S-Band antenna is slaved to the VHF antenna. Upon acquisition, the S-Band transponder begins transmitting while the S-Band receiver adopts an auto-track mode of operation. Modulation of the uplink carrier is initiated. The S-Band system is then independent of the VHF system and begins to extract range, range rate, and angle data. Using this method, data may be received by up to three stations simultaneously.

Another possible method of operation is to acquire and track at the VHF frequency. In this mode the satellite is acquired as before. Upon acquisition the uplink VHF carrier is modulated and the VHF receiver extracts the range and range rate data. The angular data is received by the S-Band antenna, which remains slaved to the VHF antenna. The system is capable of receiving data at varying rates of 8, 4, 2 or 1 time per second, or 6 times per minute, synchronized in time to within 10 microseconds of WWV reception. TABLE 3 lists the carrier frequencies used by the GRARR system.

TABLE 3

GRARR CARRIER FREQUENCIES

Transmitter	Frequency (approximate)
Satellite VHF	136 Mc.
Satellite S-Band	1705 Mc.
Ground Station VHF	148 Mc.
Ground Station S-Band	2271 Mc.

3.121 Precision range measurements are accomplished by measuring the phase shift in eight (six) coherently produced, phase modulated sidetones on the S-Band (VHF) channel. The basic sidetone frequencies are:

(S-Band only)	500 Kc.	800 cps
(S-Band only)	100 Kc.	160 cps
	20 Kc.	32 cps
	4 Kc.	8 cps

These frequencies were determined by the requirements for obtaining resolution in the measurement of phase shifts, and for resolving ambiguities. The conflict between these two requirements is discussed in Section 2.122. The low frequencies provide the ambiguity resolution capability while resolution in measurement is attained by the high frequencies.

GRR-2 utilizes a hybrid ranging system consisting of the basic sidetone system modified to incorporate ambiguity resolution by a supplementary digital code ranging signal. Two independent range measurements are made; a tone measurement and an ambiguity-resolving code range measurement. The tone measurement uses the tones from 500 Kc. to 8 cps, which provide a precise range measurement that has a minimum ambiguity equal to one-half the wave length of the 8 cps frequency (18,740 km). The ambiguity resolving code signal is then used to resolve the 8 cps ambiguities to 1,213,600 km.

The sidetone frequencies are produced coherently in the reference pulse generator, which is locked into synchronization with the digital clock. The sampling rate for range and range rate data is usually one per second, although other rates shown in TABLE 4 may be used.

The ranging frequencies phase modulate the S-Band or VHF uplink carrier. To avoid having sidetones too close to the carrier frequencies, the sidetones below 4 Kc. are combined with 4 Kc. before being used as modulation. This is to avoid difficulty in determining the Doppler shift in the carrier frequencies, which is the basis for range rate measurements.

The modulated uplink carrier is received by the transponder which transfers the modulation to the downlink carrier while maintaining phase coherence. The range tones are received by the ground station and the phase shift in each sidetone is determined.

3.122 Range rate is determined by measuring the received Doppler cycles per unit time. This is measured by timing a preset number (N_F) of cycles of the sum of the Doppler shift plus a known frequency bias. The equation for this time interval determination is

$$T = \frac{N_F}{f_B + f_D},$$

where

T = time interval for N_F cycles to be counted,

f_B = bias frequency of 500 Kc. (S Band) or 30 Kc. (VHF),

f_D = two-way Doppler shift,

N_F = preset number of cycles to be counted.

Various values of N_F for different sampling rates are given in TABLE 4.

TABLE 4

PRESET CYCLES FOR GRARR

Sampling Rate	S-Band N_F	VHF N_F
8 per second (GRR-1 only)	32,751	2,046
4 per second	65,503	4,093
2 per second	131,007	8,187
1 per second	229,263	14,328
6 per minute (GRR-2 only)	3,133,956	182,182

In order to determine the Doppler frequency, frequency coherence of the ground transmitter frequency must be maintained through the transponder and back to the ground receiver. This signal is then compared against a coherent sample of the transmitter frequency to determine the Doppler frequency.

3.13 Major Components

A simplified block diagram of the GRARR system is shown in Figure 3.1. The following gives a brief description of the major subsystems.

a. Timing Subsystem--The primary functions of the timing subsystem are to maintain time information and to provide highly accurate and stable timing signals for other subsystems. A 1 Mc. frequency standard provides stable reference frequencies for the entire system. The stability of this oscillator is better than 5 parts in 10^{10}. The oscillator is synchronized daily with WWV with corrections applied for propagation delay. The absolute time at a given station with respect to WWV is known to $\pm$ 1 millisecond.

The digital clock counts 1 Mc. pulses down to 1 pulse per second, then provides these pulses to a counter. In addition to providing time information, the digital clock is used to drive the reference pulse generator which provides synchronization of the ranging sidetones and range pulse rates with the clock.

b. Signal Generation Subsystem--The function of this subsystem is to generate coherent range tones and the hybrid code, combine those signals, and phase modulate the VHF and S-Band uplink carrier signals.

c. Transmitter Subsystem--The transmitter subsystem amplifies the tone-modulated carrier signals received

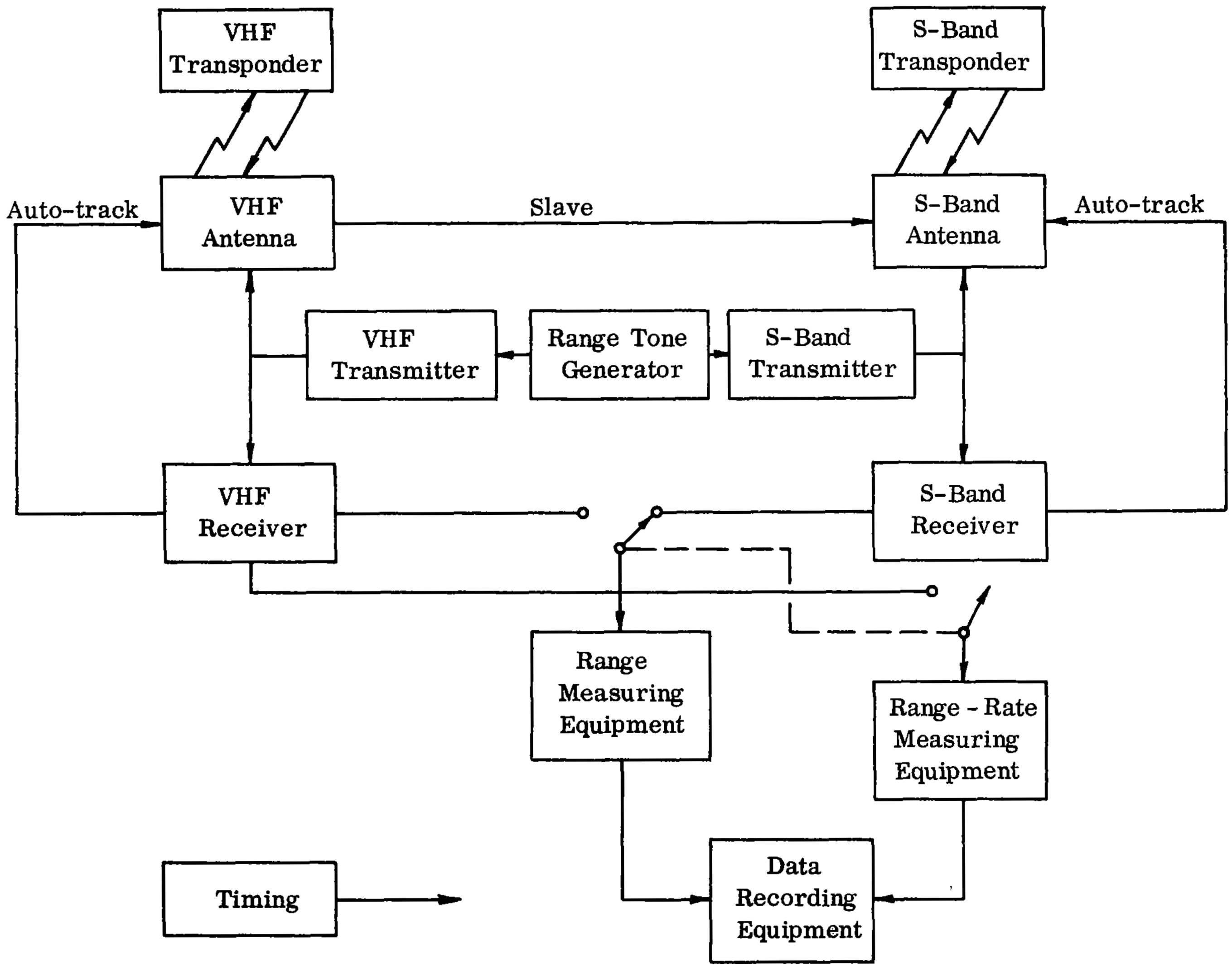


Figure 3.1. Block Diagram of GRARR System.

from the signal generation subsystem. One 10 Kw. transmitter is required for each frequency band of operation, i.e., one for VHF and one for the S-Band channel.

d. Antenna Subsystem--The antenna subsystem receives the 10 Kw. modulated carrier signals from the transmitters and radiates these signals toward the satellite. The downlink modulated carrier signals are collected and delivered by the antenna subsystem to the receiver subsystem. A separate antenna group is provided for each of the VHF and S-Band signals.

e. Receiver Subsystem--The receiver subsystem extracts Doppler and range tones from received signals. It also provides synchronous amplitude detection of the X-angle and Y-angle tracking. After extraction, range, range rate, and angle data are punched on paper tape for transmission via teletype to Goddard Space Flight Center, Greenbelt, Maryland.

f. Transponder Subsystem--Both an S-Band and a VHF transponder are carried by the satellite. The S-Band transponder consists of three channels and therefore is capable of operation with three ground stations simultaneously. In this case, the highest frequency range tone which may be used is 100 Kc., rather than 500 Kc. The VHF transponder is capable of only one-channel operation with 20 Kc. as its highest ranging tone frequency. The VHF transponder also serves as a telemetry transmitter for the satellite. The ranging function is energized by a command tone that allows the modulation to be placed on the carrier. The 4 Kc. ranging tone holds the transponder in the ranging condition until the tones are turned off, then the transponder reverts back to a telemetry transmitter.

The range, range rate, data multiplexing, and timing equipment are common to both modes of operation. This allows measurements to be made with either the VHF or S-Band channels, but not with both simultaneously.

3.14 GRARR Operations

The Goddard Range and Range Rate System presently consists of five tracking stations, all of which are incorporated into NASA's Space Tracking and Data Acquisition Network (STADAN).

Design of the original system (GRR-1) by Motorola began in 1962. Stations were installed at Rosman, North Carolina; Carnarvon, Australia; and Tananarive, Madagascar. These stations use sidetones exclusively in their range and range rate determinations.

A second generation system (GRR-2) was designed by General Electric in 1964. Stations are currently operating in Santiago, Chile, and Fairbanks, Alaska. These stations use sidetones implemented by an ambiguity resolution code for data determinations. Other changes include the addition of a 6-sample per minute data rate, and slight modifications in some of the equipment capabilities. The format of the transmitted data also varies slightly from the GRR-1 system as is shown in Section 3.2.

To date, the only satellites launched carrying GRARR transponders have been GEOS A and GEOS B.

The specified instrumental accuracies for the system are shown in TABLE 5.

TABLE 5

SPECIFIED INSTRUMENTAL ACCURACIES FOR GRARR

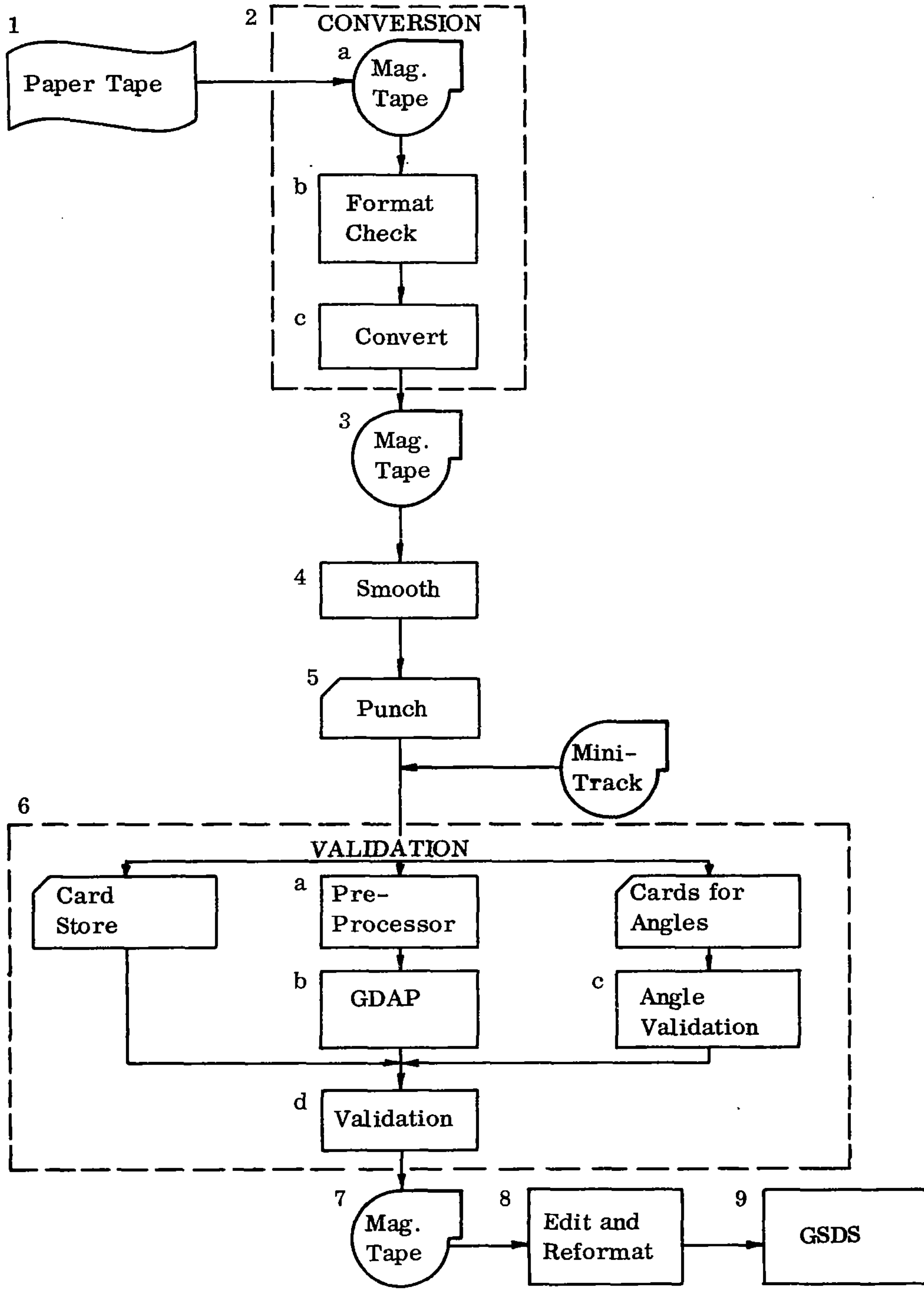
Parameter	S-Band	VHF
Range	15.0 meters rms	50.0 meters rms
Range Rate	0.1 meter per sec. rms	1.0 meter per sec. rms
Angle	0.1 degree rms	1.0 degree rms

3.2 GODDARD RANGE AND RANGE RATE DATA PROCESSING SYSTEM

3.21 Preprocessing Procedures

Data from the Goddard Range and Range Rate System (GRARR) is processed at the Goddard Space Flight Center in Greenbelt, Maryland. Figure 3.2 depicts a flow-diagram of the preprocessing steps from time of receipt from the tracking station to storage at the Geodetic Satellites Data Service, Greenbelt, Maryland. The following is a description of the flow-diagram:

1. Raw data is received from stations via teletype in the form of punched paper tape. The data in general consists of time interval measurements and angular measurements. The teletype format for one frame of the



Note: Numbers in figure correspond to numbers of descriptive paragraphs in Section 3.21.

Figure 3.2. GRARR Preprocessing Procedures.

paper tape is shown in Figure 3.3a for GRR-1 and in Figure 3.3b for GRR-2.

2a. The paper tape is used as input to a CDC 160A computer which reproduces all the data, in BCD, on magnetic tape in exactly the same format.

b. The program then checks the data for proper format and quality indicator. If data is in improper format or is of bad quality, it is rejected.

c. The same program then converts the received time interval measurements for range and range rate into units of meters and meters per second, respectively. Corrections are made for the WWV time delay to the tracking station, and for the satellite transponder delay time. The time at which GRARR signals are received from the GEOS A satellite is synchronized with UTC. Refraction corrections are not applied. A detailed description of this conversion process is given in APPENDIX C.

The four parameters (Range, Range Rate, X-angle, Y-angle) are then recorded onto magnetic tape in the standard NASA Advanced Orbital Programming Branch (AOPB) observation format. A description of this format is given in Figure 3.4.

3. The converted data is run onto magnetic tape, in the AOPB format, in blocks of up to eight frames. Each frame produces four range samples, four range rate samples, and one X-angle and Y-angle sample if X and Y are given in

Teletype format for one frame:

```
XXXXXQRRRRRRRRQṘṘṘṘṘṘṘ"DDDHHMMSSQRRRRRRRRQṘṘṘṘṘṘṘ
YYYYYQRRRRRRRRQṘṘṘṘṘṘṘ/SATSTCCCCQRRRRRRRRQṘṘṘṘṘṘṘ
                             1234
```

XXXXX	X angle of antenna position in decimal degrees (sign and 4 decimal digits given to nearest hundredth of a degree; otherwise 4"-" signs)
Q	Quality of data (a space indicates good data, a "?" indicates faulty data)
RRRRRRRR	8 digit measured time interval for range (given to nearest hundredth of a microsecond)
ṘṘṘṘṘṘṘ	7 digit measured time interval for range rate (given to nearest tenth of a microsecond)
DDD	Day of year (January 1 = 001)
HHMMSS	Hour-minute-second (time at beginning of frame)
YYYYY	Y angle of antenna position in decimal degrees (sign and 4 decimal digits given to nearest hundredth of a degree; otherwise 4"-" signs)
SAT	3 digit satellite number
ST	2 digit station number
C1	Ambiguity and resolution switch
C2	Recording rate and punch indicator
C3	Frequency indicator (S-Band or VHF)
C4	Range counter frequency (10 Mc. or 100 Mc.)

NOTE: Prior to the actual data shown above, in each line are three characters to indicate carriage return, line feed, and figure shift. This allows the punched tape to be compatible with a teletype printer.

An explanation of the above data appears in paragraph 1 of APPENDIX B.

Figure 3.3a. Punched Paper Tape Format (GRR-1).

Teletype format for one frame:

XXXXXQRRRRRRRRBṘṘṘṘṘṘṘ"DDDHHMMSSQRRRRRRRRBṘṘṘṘṘṘṘ
YYYYYQRRRRRRRRBṘṘṘṘṘṘṘ/SATSTCCNNQRRRRRRRRBṘṘṘṘṘṘṘ
1212

XXXXX	X angle of antenna position in decimal degrees (sign and 4 decimal digits given to nearest hundredth of a degree; otherwise 4 "-" signs)
Q	Quality of data (See explanation)
RRRRRRRR	8 digit measured time interval for range (given to nearest hundredth of a microsecond)
B	Quality of data, or extra range rate digit (See explanation)
ṘṘṘṘṘṘṘ	7 digit measured time interval for range rate (given to nearest tenth of a microsecond)
DDD	Day of year (January 1 = 001)
HHMMSS	Hour-minute-second (time at beginning of frame)
YYYYY	Y angle of antenna position in decimal degrees (sign and 4 decimal digits given to nearest hundredth of a degree; other wise 4 "-" signs)
SAT	3 digit satellite number
ST	2 digit station number
C1	Frequency indicator (S-Band or VHF)
C2	Recording rate indicator and resolution switch
N1	Range Ambiguity Number (See explanation)
N2	Range Ambiguity Number (See explanation)

NOTE: Prior to the actual data shown above, in each line are three characters to indicate carriage return, line feed, and figure shift. This allows the punched tape to be compatible with a teletype printer.

An explanation of the above data appears in paragraph 2 of APPENDIX B.

Figure 3.3b. Punched Paper Tape Format (GRR-2).

Range Record Column	Contents
1	Space
2-6	Satellite identification
7	Space
8-13	Station label
14	Space
15-20	Date (year-month-day)
21	Space
22-25	Hour-minute
26	Space
27-32	Second and fraction
33-48	Spaces
49-57	Range in meters
58-67	Spaces
68	Zero (0)
69	Space
70	One (1)
71	Space
72	C_1

Range Rate Record Column	Contents
1-32	(Same as for range)
33-57	Spaces
58-64	Sign and range rate in meters/second with decimal between col. 62 & 63
65-68	Spaces
69	Zero (0)
70	One (1)
71	Space
72	C_1

Figure 3.4. AOPB Format.

X Angle Record Column	Contents
1-32	(Same as for range)
33	Sign (+ or -)
34-40	X angle with decimal between col. 36 & 37
41-65	Spaces
66	Zero (0)
67-69	Spaces
70	Seven (7)
71	Space
72	C_1

Y Angle Record Column	Contents
1-32	(Same as for range)
33-40	Spaces
41	Sign (+ or -)
42-47	Y angle with decimal between col. 43 & 44
48-66	Spaces
67	Zero (0)
68-69	Spaces
70	Seven (7)
71	Space
72	C_1

The last record of each block of reduced data will contain a nine (9) in column 1 to denote the end of block. The (9) may appear either on the last range rate record or on the last Y record if Y data are present.

Figure 3.4. (Cont'd.).

the raw data. Each data sample produced makes one BCD record on magnetic tape, so one frame may yield either eight or ten records, depending on whether the X and Y angle values are given.

4. The magnetic tape is used as input to a CDC 3200 computer for a smoothing program. The range and range rate data are fitted to a second degree polynomial of the form

$$F(t_i) = A_o + A_1 t_i + A_2 t_i^2$$

using the method of least squares. The fit is made to a block of data consisting of up to 32 samples of range, 32 samples of range rate, 8 samples of X, and 8 samples of Y. In the process of this smoothing, samples are rejected on the basis of a 2.0σ criterion (σ is the rms of the observed data points) and are not used in the determination of the polynomial coefficients. Either one of two convergence tests must be met:

1) No samples are rejected,

2) σ becomes less than a preset minimum (200 meters for range; 2.0 meters/sec. for range rate).

There must be at least five good range points and five good range rate points in the fit for the data to be accepted.

The smoothed data point is given to be t_m and $F(t_m)$, where t_m is taken to be the time of the middle (16th) sample in the block of data.

To maintain maximum computational accuracy the raw time values, t_i, and the corresponding data values, D_i, are normalized about the midpoint values t_m and D_m, respectively. This is done in the following manner:

The abscissa and ordinate values are defined as

$$X_i = t_i - t_m, \text{ and}$$

$$Y_i = D_i - D_m.$$

Application of the method of least squares yields

$$Y_i = A_o + A_1 X_i + A_2 X_i^2.$$

Since

$X_m = 0$ when $t_i = t_m,$ then $Y_m = A_o.$

The smoothed data, $F(t_m)$, is therefore

$$F(t_m) = D_m + A_o.$$

This smoothing is applied to consecutive sets of 32 samples; it is not a moving arc fit.

5. Each smoothed parameter is punched on a card in the AOPB format. Cards are used so that the data can be separated, if desired, by time interval or by satellite. The punched cards are then used for validation of the data.

6. The purpose of the validation process is to determine whether the smoothed data is of acceptable quality to be stored at the Geodetic Satellites Data Service. Tapes containing Minitrack data are used as input, along with the punched cards. The process can be divided into

the following steps:

a) The GDAP Preprocessing Program is run on the CDC 3200 computer. The purpose of this program is to provide the main GDAP program with a set of initial orbital elements (X, Y, Z, $\dot{X}$, $\dot{Y}$, $\dot{Z}$) for the epoch time of each data set. The Preprocessing Program extracts these elements from orbit generator routine minute vector tapes (MVT) which result from Minitrack observations. Minute vectors are geocentric inertial cartesian coordinates provided for every minute. The preprocessing program then stores this data in the format required for GDAP.

b) The GEOS Data Adjustment Program (GDAP) is run on the CDC 3200 computer. Its function is to fit the GRARR data to an orbit calculated from the Minitrack Orbital elements. This is accomplished by calculating an approximate solution to a series of normalized simultaneous equations. The program determines a simultaneous solution to all equations used to describe the orbital motion of the satellite. The solution is one which minimizes the weighted sum of squares of the discrepancies between these equations and the actual observations.

The general mathematical structure used in the solution is

$$F_j = \sum_i [w_i f_i (X_j, Y_j, Z_j, \dot{X}_j, \dot{Y}_j, \dot{Z}_j, T_j, P_1 \ldots P_n)]^2 ,$$

where

w_i = weight based on *a priori* standard error input,
f_i = ($data_i$ observed - $data_i$ computed),
X_j, etc.= orbital parameters,
T_j = (observation time - epoch time),
P.... = error model parameters which account for zero set bias, timing error, etc.

After linearization by a Taylor's Series expansion, an adjustment is performed by variation of parameters. The solution is then used to update the approximate error model coefficients. The process is iterated until the corrections are less than, or equal to, one-half the *a posteriori* standard error estimates [RCA Service Company, 1967].

Before comparing the computed orbital parameters with the observed data, a tropospheric refraction correction is applied to the observed data. The correction is based on the model formulated by D. Brown [Brown, 1966]. This correction is applied only for validation purposes and is not incorporated in the data sent to the GSDS. No ionospheric refraction correction is applied.

The program output consists of the residuals between the observed data (range and range rate) and the updated values of the orbital parameters.

c) The GRARR Angle Validation Program is run on the IBM 7094 computer. Values for the X- and Y-angles are validated by comparing them with values obtained from *post factor* Minitrack orbit data.

Input to this program consists of the following two quantities:

(1) Control cards giving values of station coordinates, semimajor axis and eccentricity of the earth's reference ellipsoid, and the rejection limit for each angle.

(2) The punched cards with the smoothed GRARR data are also used as input; however, only the X- and Y-angle records are processed; the other records are skipped.

The Minitrack data used for comparison is on the same minute-vector tapes mentioned in par. 6a. The minute vector tape (MVT) is scanned for times corresponding to the X- and Y-angle times. The MVT data is then interpolated up to the exact time of the X- and Y-angle. The MVT geocentric inertial cartesian coordinates are transformed to topocentric cartesian coordinates [Mueller, 1964], and then to X and Y angles by the formulas

$$X = \text{ARCTAN } (E/V), \text{and}$$

$$Y = \text{ARCTAN } [N/(E^2+V^2)^{1/2}],$$

where E, N, V are topocentric cartesian coordinates of the satellite. The corresponding angles are then compared and, if accepted, the process is repeated for the next X- and Y-angle. If either or both the angles are not within the required tolerance (±1°) when compared to the MVT data, a card is punched containing station name, date and time of observation, and value of the residual(s). If both the X-angle and Y-angle are unacceptable, a "1" is punched in column 71. These cards are used as input to the GRARR Validation Program.

d) The GRARR Validation Program is run on the CDC 3200 computer. The purpose of this program is to place a data quality flag on each data record, indicating whether that item of data should be withheld from the Geodetic Satellites Data Service. The flag is placed in column 71 of each record. The quality indicator can have the following values:

0 - acceptable data,

1 - unacceptable data,

2 - ambiguous data (range), acceptable data after ambiguity correction,

3 - ambiguous data (range), unacceptable data after ambiguity correction,

4 - unacceptable X angle,

5 - unacceptable Y angle.

A flag is placed in column 1 of each data record to indicate the S-Band transponder subchannel, A or C, from which the data was obtained. These flags are as follows:

0 - Channel A (2271.9328 Mc.),

2 - Channel C (2270.1328 Mc.).

The input to this program consists of the original GRARR data cards, the range and range rate residuals punched from GDAP, a card for each X- or Y-angle that is in error, and a set of control cards for each pass. The first control card for each pass contains the rms values for range and range rate as given by GDAP and the number of ambiguities, if any, present in the range data. If, for some predetermined reason, all range data, all range rate data, or an entire pass is to be withheld, a control card with one of the following flags in column 73 is used:

1 - flag all range data unacceptable,

2 - flag all range rate data unacceptable,

3 - flag entire pass unacceptable.

If the acceptability of the data for a given pass has not been predetermined, certain internal rejection criteria are used in the program. For range data, a limit of 30 meters or three times the range rms from GDAP, whichever is less, is used; while for range rate, 0.5 meter per second or three times the range rate rms is used [RCA Service Company, 1967]. Any data point exceeding the above limits would be flagged on the original GRARR data cards as an unacceptable data point. Each X- and Y-angle is checked against the X- and Y-angle cards produced by the Angle Validation Program. If a match is found, the X- or Y-angle is flagged in column 71 as unacceptable.

7. The final validated data, flagged for quality and channel number, are placed on BCD magnetic tape in AOPB format. Each tape has a single end of file mark following the final validated data record.

8. The magnetic tape is used as input to the CDC 3200 computer where an edit and reformat program performs the following two functions:

a) All data card images are removed which have a number other than zero in column 71 (bad data),

d) Data card images are converted from AOPB format to the required format for the National Geodetic Satellite Program. This format is shown in APPENDIX A for range determinations, and in APPENDIX D for range rate data.

9. Magnetic tapes in the proper format are submitted to the GSDS.

3.22 <u>Corrections to Data</u>

3.221 The following corrections are applied to GRARR data during preprocessing:

1. Propagation delay from WWV

This correction is applied during the conversion process described in Par. 2c, Section 3.21. The values for the delay to the different stations are as follows:

STATION		PROPAGATION DELAY (sec.)	
Number	Name	Before 12/1/66	On or after 12/1/66
26	Rosman	.0036	.00763
22	Tananarive	.0489	.05772
52	Carnarvon	.0383	.0383
28	Fairbanks		.01349
27	Santiago		.03164

Change in propagation times was due to movement of WWV from Greenbelt, Md., to Ft. Collins, Colorado.

Carnarvon is referenced to WWVH, Hawaii.

2. Effective Transponder Delay

This correction is applied during the conversion process described in Par. 2c, Section 3.21. The value of this correction is determined by pre-launch tests of each transponder channel. The portion of the correction due to pole beacon simulator delay, T_p, is not currently applied so that the entire correction is due to the transponder delay, T_D, only. Values for the correction are given in the above mentioned paragraph.

3.222 The following corrections remain to be applied to GRARR data in the GSDS. The numerical values listed are those used at Goddard Space Flight Center for the GEOS Observation Systems Intercomparison Investigation [Berbert, 1967].

A. Corrections to Range Data

1. Refraction Correction

The following refraction model was formulated by J. J. Freeman Associates Inc.:

$$C_R = \frac{1}{\text{Sin } E}\left[\int_0^\infty N dh - \frac{\text{Cot}^2 E}{r_o} \int_0^\infty N h dh\right],$$

where

C_R = refraction correction to be subtracted from the measured range,

E = elevation angle of satellite,

r_o = earth radius,

N = refractivity index.

a. Tropospheric Refraction Correction

For the troposphere, the integrals can be represented in closed form as follows:

$$C_R = \frac{1}{\text{Sin } E}\left[\frac{Ns}{k} - \frac{\text{Cot}^2 E}{r_o}\left(\frac{Ns}{k^2}\right)\right],$$

where

N_s = station ground index of refraction,

K = a tabulated function of N_s as found in "CRPL Exponential Reference Atmosphere" by Bean and Thayer.

b. Ionospheric Refraction Correction

For this correction, the integrals are represented by the following closed forms:

$$C_R = \frac{1}{\text{Sin } E}\left[HN_m e - \frac{\text{Cot}^2 E}{r_o}\left(H^2 N_m e\left(1 + \frac{h_m}{H}\right)\right)\right],$$

where $H = 1.66\ [30 + .2\ (h_m - 200)]$ km,

$h_m = 1393.1 \exp(-.5014\ M)$ km,

$M = \frac{\text{MUF (3000)}}{F_o}$ (Both values are obtained for a given month and position from the CRPL Ionospheric Prediction Map),

MUF = maximum usable frequency at 3000 km,

e = 2.71828,

F_o = plasma frequency at the maximum in Mc./sec.,

$N_m = .502\left(\frac{F_o}{F_{eq}}\right)^2$ (This is maximum index of refraction at frequency F_{eq}),

F_{eq} = 1928 Mc. This equivalent frequency is used due to the difference in the uplink and downlink carrier frequencies [Berbert, et al., 1967].

2. Antenna Position Correction

The GRARR antennas are mounted on an X-Y system as defined in the Goddard Directory of Tracking Station Locations, 1964. The X-axis is oriented north-south and is fixed. The Y-axis is oriented east-west but is mounted above the origin of the X-axis. This causes the Y-axis position to vary sinusoidally with respect to the geodetic site location. The correction is added to the measured range and is represented by

$$C_Y = d \cos Y,$$

where Y = Y-angle of the antenna,

d = distance above the X-axis (1.17 meters at Rosman).

3. Zero Set Correction

This correction is added algebraically to the measured range and is necessary because of the equipment bias at each ground station. The total correction accounts for the bias in various components, including transponder horn aperture, cabling delays, boresight calibration, and boresight parallax. The following values are the zero set corrections used at each station:

Rosman: C_o = 9.7 meters,

Tananarive: C_o = 7.9 meters (before 2/18/66 1300Z)

= 25.9 meters (2/18/66 to 11/7/66 1300Z)

= -1.1 meters (after 11/7/66 1300Z),

Carnarvon: $C_o = -1.1$ meters,

Fairbanks: Undetermined,

Santiago: Undetermined.

4. Timing Correction

A partially unexplained timing error of -1.6 milliseconds was noticed in data taken in August-November 1966. The error may be due to an offset in the transponder oscillator; however, it is not clear whether this was a permanent malfunction. It is recommended [Berbert, 1967a] that a correction of 1.6 milliseconds be added to the time (T_{RM}) of each range measurement for GEOS-A taken on channel A.

5. Transponder Delay Correction

This correction is a function of the range rate of the satellite and is not accounted for by the constant transponder delay correction (T_T) incorporated during preprocessing. The following corrections are to be subtracted from the measured range for GEOS-A [Berbert, 1967a]:

Channel A (F_u = 2271.1328 Mc.)

$$C_A = (7.18 \times 10^{-8})\,\dot{R}^2 + (3.32 \times 10^{-4})\,\dot{R}, \text{ and}$$

Channel C (F_u = 2270.1328 Mc.)

$$C_C = (1.82 \times 10^{-15})\dot{R}^4 - (4.42 \times 10^{-12})\dot{R}^3 - (8.34 \times 10^{-8})\dot{R}^2 - (5.22 \times 10^{-4})\dot{R},$$

where F_u = uplink carrier frequency for a given channel,

$\dot{R}$ = satellite range rate in meters per second.

B. Corrections to Range Rate Data

1. Refraction Correction

A model for the total refraction correction for GEOS A, as formulated by Freeman, is shown as follows:

$$C_R = \frac{\text{Cos } E}{\text{Sin}^2 E} \dot{E} \left[\left(\int_o^\infty N dh + \frac{Ns}{k} \right) + \frac{3}{\frac{1-\text{Sin}^2 E}{r_o}} \left(\int_o^\infty Nhdh + \frac{Ns}{k^2} \right) \right] ,$$

where

C_R = refraction correction to be added to measured range rate,

$\dot{E}$ = elevation rate of satellite.

The integrals are as defined in Par. A1b, Section 3.222, with Feq = 3648 Mc. A value for an equivalent frequency is necessary since the uplink carrier travels with phase velocity while the downlink carrier travels with group velocity [Berbert, et al., 1967].

2. Timing Correction

For the same reasons as stated in Par. A4, Sec. 3.222, it is recommended [Berbert, 1967a] that a correction of .2 milliseconds be added to the time ($T_{\dot{R}M}$) of each range rate measurement for GEOS-A taken on channel A.

3. Antenna Motion Doppler Correction

This correction should be added to the range rate measurement. For GEOS-A, the maximum value of the correction is about .2 cm/sec., and is computed by

$C_{\dot{Y}}$ = -1.17 $\dot{Y}$ SIN Y meters per second,

where

$\dot{Y}$ = rate of change of antenna Y angle.

4. Range Rate Averaging Correction

This correction is caused by the error in approximating the instantaneous value of range rate by the average value over the interval ΔT. For GEOS-A, the maximum correction is about .7 cm/sec., and is computed by

$$C_A = \frac{-\dddot{R}\,(\Delta T)^2}{24},$$

where

C_A = correction to be added algebraically to the measured range rate,

$\dddot{R}$ = third time derivative of range.

3.3 DISCUSSION

As can be seen from Section 3.222, GRARR data in the GSDS as of 1 November 1967 is not free of all systematic errors; the main errors remaining are due to refraction, zero set, and timing. Work is currently being done to more accurately determine these errors so that they may be accounted for in the processing of data. Some of the corrective measures currently being taken are [Berbert, 1967a]:

1. Measurement of pressure, temperature, and humidity at the ground stations. This will allow a more accurate determination of the station index of refraction, N_s, used in the refraction correction.

2. Pre- and post-calibration will be performed at ground stations to more accurately determine equipment bias.

3. Measurement of transponder temperature will be used to more accurately determine transponder delay.

4. Additional data quality factors will be measured, including: solar activity, weather, and hardware difficulties.

No generally accepted error model is currently used to account for the systematic errors; however, the current GEOS Observation Systems Intercomparison Investigation has produced the following provisional error models [Berbert, et al., 1967]:

<u>Range Error Model</u>

$$\Delta R = K_7 \cdot \dot{R}^2 + K_6 \dot{R},$$

where

ΔR = systematic error in range,

K_7 = servo lag error = .14 ± .10 seconds,

K_6 = range timing error = undetermined.

No refraction term,or zero set term, is used since the corrections were applied (Par. 1, Sec. 3.222) for intercomparison purposes. A general error model for range determinations is given in Section 6.

<u>Range Rate Error Model</u>

$$\Delta \dot{R} = K_5 C_R + K_1 \dot{R} + K_2 \ddot{R} + K_4 \dot{R} \ddot{R},$$

where

$\Delta\dot{R}$ = systematic error in range rate,

$C_R = \frac{\dot{E} \text{ COS } E}{\text{SIN}^2 E}$,

K_5 = range rate refraction error = $-.7 \pm .5$ cm/sec.,

K_1 = transmitter frequency error = -11 ± 2 parts per million,

K_2 = range rate timing error = $.21 \pm .01$ milliseconds,

K_4 = transponder delay = $-.33 \times 10^{-6} \pm 2.6 \times 10^{-8}$ sec.^{2}/meter.

The refraction term refers to residual refraction, since the correction was applied for intercomparison purposes. A general error model for range rate determinations is given in Section 6.

The GRARR data currently in the GSDS represents the smoothed parameter from 32 samples. For the usual recording rate of 1 sample per second, the smoothed parameters would be at 32-second intervals. However, because of the editing performed in the validation process (Step 6, Figure 3.2) the time gaps are much larger. It is estimated [RCA Service Company, 1967] that only 55% of GEOS-A data passed through the validation process flagged as acceptable for the GSDS. The same report states that, in the GDAP validation, the small percentage of acceptable data may be due to:

1. Excessive dependence on range rate data in the validation process.

2. Lack of range rate bias terms in the orbital solution.

3. Unrealistic rejection criteria.

One solution to the problem of storing only a small amount of the original data would be to store raw data in the GSDS, and let each investigator use his own corrections and reduction method. This would require greater storage space and might burden the GSDS with quantities of poor or useless data.

A better solution might be to process the raw data through a slightly more liberal validation process, then store the validated data, selected from a more convenient interval (1 to 5 sec. between samples), in the GSDS.

4. LASER RANGING SYSTEMS

4.1 GENERAL SYSTEM DESCRIPTION

4.11 Introduction

In addition to the electronic distance measuring equipment used in satellite tracking, laser ranging systems have become practical since the launch of certain satellites equipped with retroreflectors. Laser systems appear to have the following advantages over electronic ranging systems [Anderson, et al., 1967c]:

1. The satellite retroreflector is a passive device, requiring no electrical energy from the satellite.

2. Lasers generate peak powers of hundreds of megawatts as opposed to less than 10 megawatts for radar devices. This large power pulse permits laser range measurements at distances of megameters.

3. Lasers produce pulses whose lengths are only tens of nanoseconds, thus lending themselves to precise range measurements.

4. Laser ranging systems transmit in the visible wave length region, therefore ionospheric propagation effects are not observed. Also, the tropospheric refraction correction does not have to account for the effects

of atmospheric water vapor.

One disadvantage of laser systems is the reduced sensitivity of their receivers. This is because the quantum efficiency of phototubes is only a few percent at the laser's wave length, and because the higher energy of a single quantum increases the minimum signal that can be detected. Another disadvantage is that an optical system is usually inoperative in cloudy weather.

4.12 Operational Laser Systems

There have been three laser ranging systems in operation: those operated by Goddard Space Flight Center (GSFC) at Greenbelt, Maryland and Rosman, North Carolina; the Smithsonian Astrophysical Observatory (SAO) station at Organ Pass, New Mexico; and the French systems in France, Greece, and Algeria. The Smithsonian station operated until July, 1967 and is currently being dismantled. A new station will be operational in early 1968 at Mount Hopkins, Arizona. TABLE 6 gives the characteristics of the various systems [Anderson, et al., 1967b].

TABLE 6

LASER RANGING SYSTEM CHARACTERISTICS

	GSFC	French	SAO	
			Organ Pass	Mt. Hopkins
Type Laser		All use Q-switched Ruby Laser		
Wave Length (nm)	694.3	694.3	694.3	694.3

TABLE 6 (CONT'D)

	GSFC	French	SAO	
			Organ Pass	Mt. Hopkins
Tracking Method	Preprogrammed tape	Visual	Visual	Orbit predictions
Pulse Duration (nsec.)	10-30	20-30	40-60	10
Power Output (Mw.)	25	30	8	500
Pulses per min.	60	15	2	4
Transmitter beam width (mrad.)	1	1	1	.58-5.8
Receiver aperture diameter (inches)	15	14	11	20
Receiver band width (nm)	10	1.8	7	.6
Receiver beam width (mrad.)	1.5-5	1	1	.58-5.8

The French system will not be discussed further.

There have been five satellites launched with retroreflectors which may be used by the above ranging systems. TABLE 7 lists these satellites.

TABLE 7

SATELLITES WITH RETROREFLECTORS

Name	Designation	Inclination (degrees)	Apogee (Mm)	Perigee (Mm)
BE-B	1964-64A	80	1.1	0.9
BE-C	1965-32A	41	1.1	0.9
GEOS-A	1965-89A	59	2.3	1.1
D1-C	1967-11A	40	1.4	0.6
D1-D	1967-14A	39	1.9	0.6
GEOS-B	1968-02A			

GEOS-A was stabilized in attitude by the earth's gravity gradient. One face is always oriented vertically downward and on this is mounted a flat array of retroreflectors. The other satellites are constrained by means of a magnet, which orients them along the earth's magnetic field.

4.13 Principles of Operation

Laser systems measure the time interval required for a laser pulse to travel from a transmitter to the satellite and back to a receiver. Range to the satellite is then determined by multiplying this time interval by one-half the velocity of light in a vacuum. Corrections must be applied to the range due to system delays and refraction.

Laser ranging systems now in operation utilize a pulsed ruby laser. Figure 4.1 is a representation of an air-cooled laser transmitter used for geodetic purposes. (Latest types of transmitters are more sophisticated than the drawing indicates.) A general description of the transmitter operation is as follows: a triggering pulse fires a xenon flash lamp which in turn causes excitation of the ruby rod. The excitation is caused by the fact that the bound electrons in the ions of the ruby crystals are stimulated to a process of emission when receiving the incident radiation of the flash lamp. In order to prevent an irregular type oscillation of the ruby rod, maximize the power output, and minimize the pulse duration, a Q switching mechanism is inserted into the optical train of the transmitter. The Q switch consists of a total

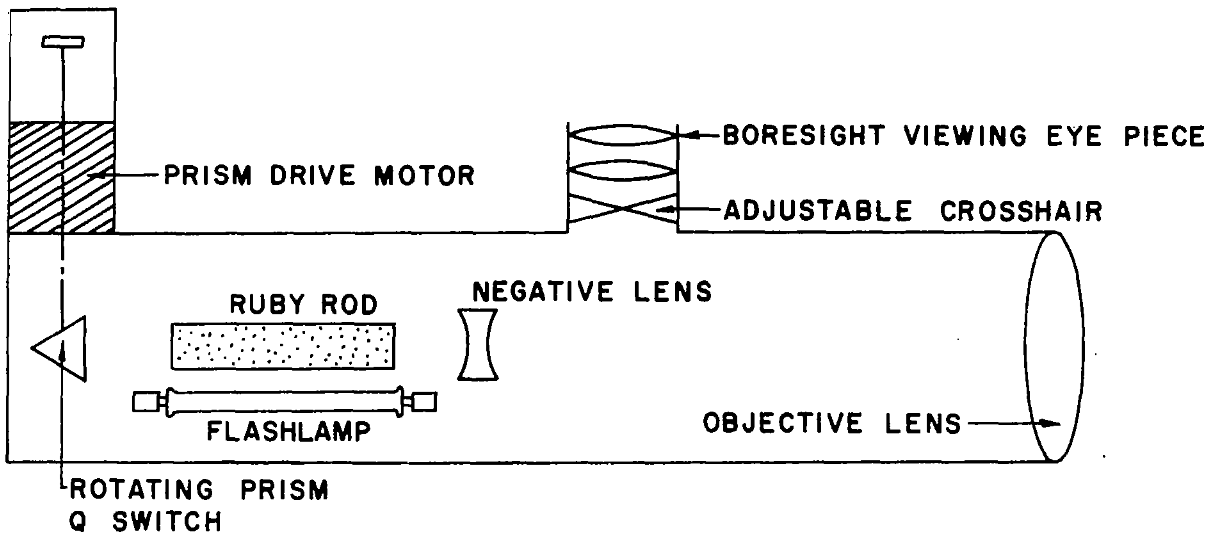


Figure 4.1. Schematic Representation of Laser Transmitter.

internal reflection prism which is rotated by a DC motor. At the instant when the rotating prism is in a position to complete the optical circuit, a giant pulse results which causes a peak power emission from the ruby rod. A magnetic pickup is used to sense the position of the rotating prism with respect to the ruby axis. A simple Galilean optical system reduces the divergence of the laser beam. A bore-sight allows the transmitter to be aligned parallel to the opto-mechanical axis of the tracking pedestal.

4.131 The following is a description of the operation of the laser system at Organ Pass, New Mexico, which was operated by SAO from June 1965 to July 1967. A simplified block diagram of the SAO Laser System which operated at Organ Pass is shown in Figure 4.2.

The laser itself is attached to a Naval gun mount. Two observers acquire the satellite by presetting predicted values of satellite azimuth and elevation. When the satellite comes within the fields of view of their telescopes, they begin to track it visually and continue until it can no longer be seen. The satellite can be visually tracked to within one or two minutes of arc. The operation of the laser is governed by the station clock. This clock fires the laser every 30 seconds at epochs that are known through the use of a time interval counter to within 100 micro-seconds. The time interval counter measures the delay in firing due to the rotating Q-switch mechanism (see Section

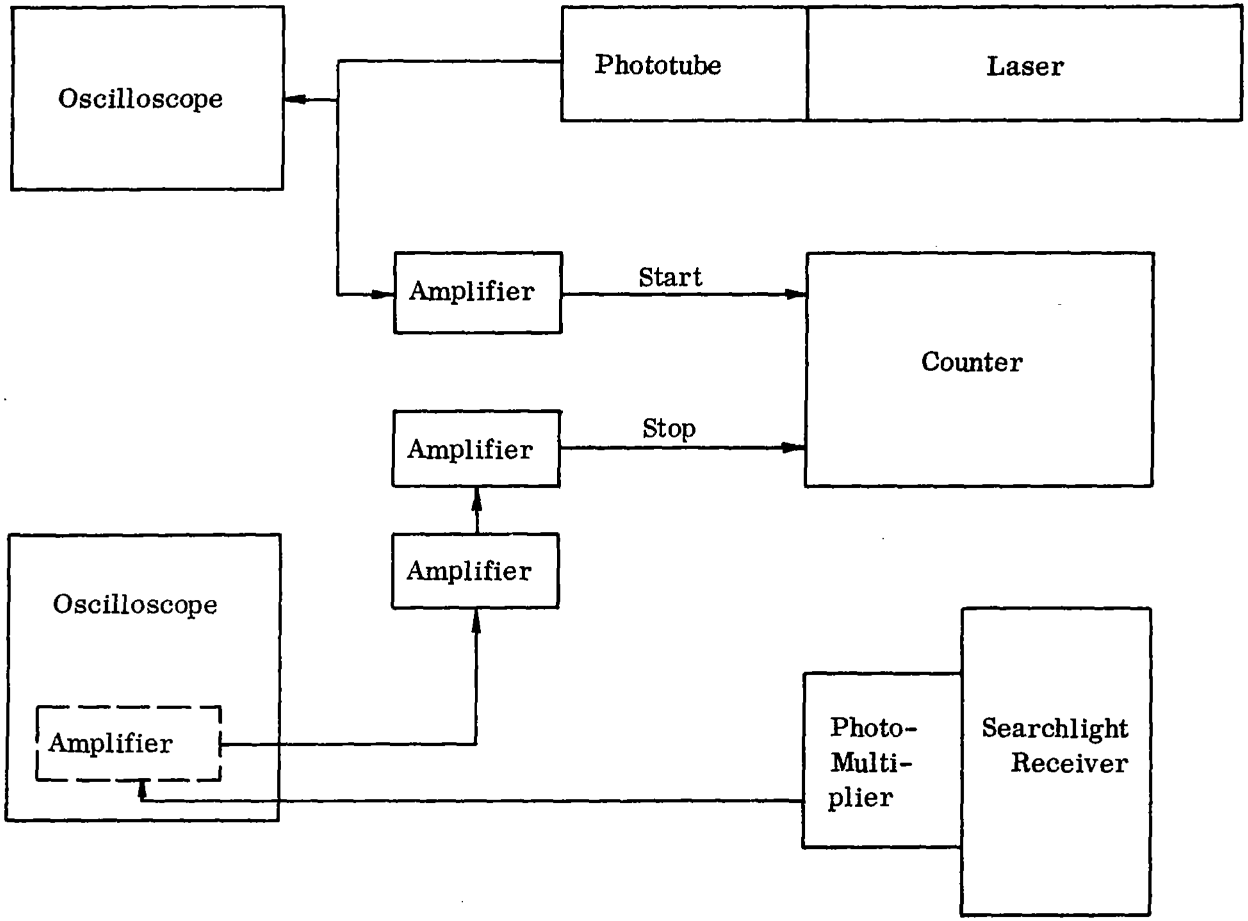


Figure 4.2. Block Diagram of SAO Laser Ranging System.

4.221). The clock also provides an accurate 1 MHz. synchronizing signal for measuring the travel time of the laser pulse to the satellite and back. The 1 MHz. signal is used by an electronic time interval counter to obtain an accuracy of ± 10 nanoseconds. The transmitted and received laser pulses are also presented on oscilloscopes.

4.132 The following is a description of the laser operated by GSFC. A simplified block diagram of the GSFC Laser System is shown in Figure 4.3.

The laser is mounted on a modified Nike Ajax radar pedestal. The aiming of the laser is accomplished by a computer driven tracking mount. The preprogrammed drive tape contains the predicted satellite azimuth, elevation, and range for each second of time. Although the tape controls the tracking apparatus, visual corrections may be made. In addition to the laser apparatus, the tracking mount is equipped with an optical telescope whose output light is detected with a photodetector. During a pass where the satellite is sunlit or flashing its lights, the output of the telescope photodetector indicates whether proper tracking is being accomplished. The pointing accuracy of the tracking system is about ± .2 milliradians.

A digital clock controls the operation of the laser transmitter and measures the instant at which it fires. At the initiation of each pulse a driver circuit starts a 100 MHz. time interval recorder. The received pulses are detected

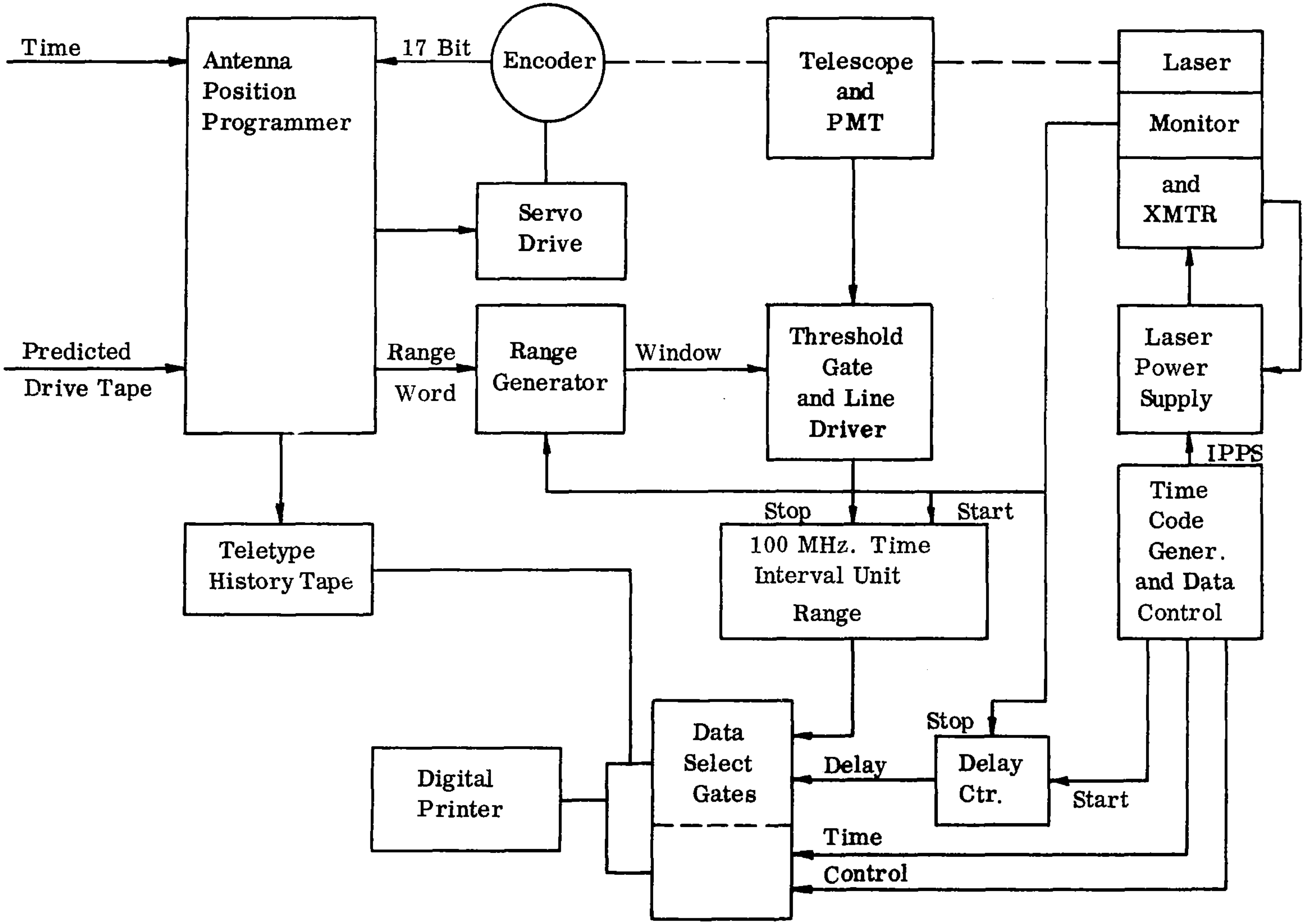


Figure 4.3. Block Diagram of GSFC Laser Ranging System.

with a high gain photomultiplier tube which triggers another driver circuit. If this driver pulse is of sufficient amplitude it triggers a threshold detector whose output stops the time interval recorder. The time interval is then punched on paper tape.

The laser transmitter is fired once per second. The rotating prism Q switching mechanism, which is run by a DC motor, cannot maintain exact synchronization with the triggering pulse. This causes a delay between the triggering signal and the actual firing of from 8.5 to 11 milliseconds. To detect this delay, a delay time interval counter is incorporated in the data control unit. This counter is started by the triggering pulse and stopped by the actual laser signal being transmitted. This time interval counter gives the absolute time of firing to within 100 microseconds.

The elevation is measured by a 17 bit optical shaft encoder, mounted on one end of the elevation axis of the tracking pedestal. On the azimuth axis is mounted a 17 bit azimuth shaft encoder.

4.14 Major Components

The major components of a laser ranging system are the transmitter, receiver, and retroreflectors. The following is a brief description of these components. System representations are shown in Figures 4.2 and 4.3.

4.141 The transmitter assembly contains the ruby rod and xenon flashlamp, both of which are contained in a water jacket tube. (SAO system at Organ Pass was air cooled.) Also within the transmitter are the Q switching mechanism described in Section 4.13, the optical system, and bore-sight features for calibration.

4.142 The receiver in the SAO system at Organ Pass was a 60 inch searchlight modified to have a Cassegrain configuration. The secondary mirror produced a beam of parallel rays that would strike the interference filter in front of the photo tube at normal incidence. Four inch telescopes were used for aiming the receiver.

The GSFC laser system receiver consisted of a 16 inch aperture, 300 inch effective focal length Cassegrain telescope. Behind the telescope is an adjustable iris followed by the photomultiplier housing and an interference filter.

4.143 The satellite-mounted retroreflectors are individual cube corner prisms. The prisms are of radiation resistant fused silica with silvered reflecting surfaces, cut at the corners to yield hexagonal faces. The prisms are approximately one inch in diameter, and are mounted on reflecting panels on the outer surface of the satellite.

4.2 SAO LASER DATA PROCESSING SYSTEM

4.21 Preprocessing Procedures

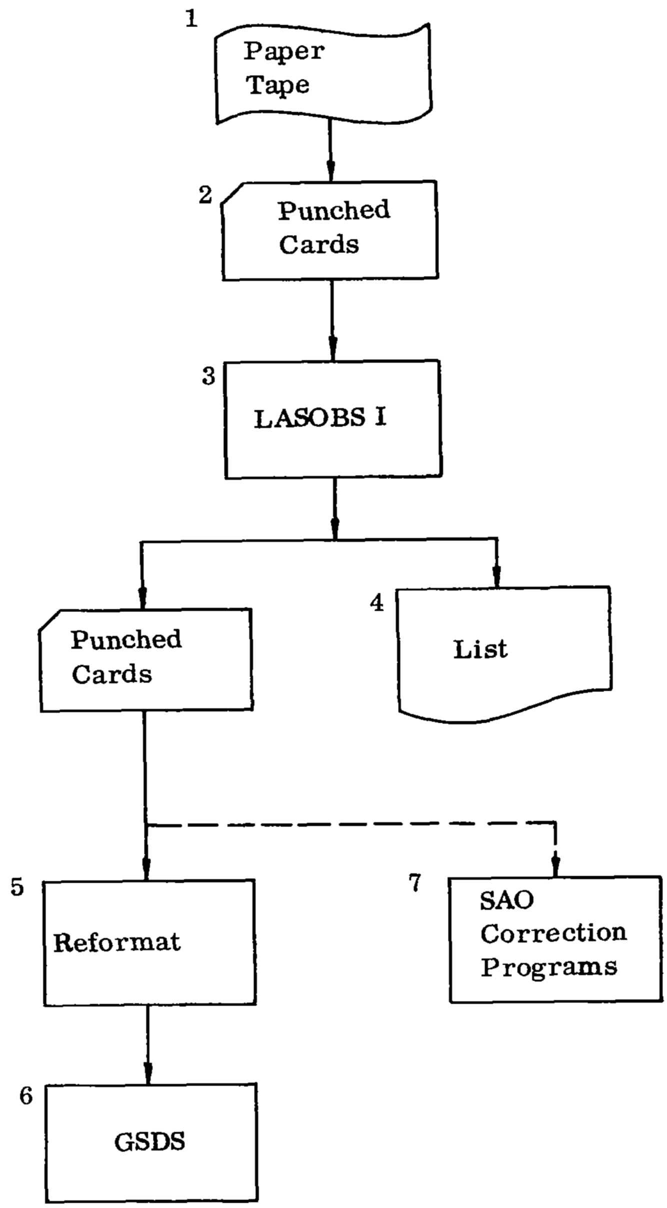
All ranging data from the SAO Laser which is in the Geodetic Satellites Data Service was observed at Organ Pass, New Mexico and processed at Cambridge, Mass. Figure 4.4 depicts a flow-diagram of the preprocessing procedures from time of receipt until data is deposited in the GSDS. The following is a description of the flow diagram.

1. Data is received from the tracking station via teletype in the form of punched paper tape. The format of the received paper tape is shown in Figure 4.5. The data is corrected for the time delay in the laser system at the tracking station prior to transmission via teletype (see Sec. 4.221).

2. The punched tape is run on an IBM 047 which converts the data to punched cards. The card format is exactly the same as was on the received tape, with one line of data from the tape (one observation) being punched on one card. The cards are then used as input to the LASOBS I Program.

3. The input to the LASOBS I Program consists specifically of:

a. A card which gives the observation number of the first observation in the first five columns.



Note: Numbers in figure correspond to numbers of descriptive paragraphs in Section 4.21.

Figure 4.4. SAO Laser Preprocessing Procedures.

The following is a typical received teletype format at SAO:

```
LAS01 60127
65089 01000 03432 00045 00001 27970 00099 97479 73785
            03442 00022 00001 12040 00099 97479 02863
```

	Data from Organ Pass	Data from Mt. Hopkins
Line 1		
WORD 1	LAS denotes laser obs. 01 denotes station no.	SAME
WORD 2	Year, month, day (27 Jan.66)	SAME
Line 2		
WORD 1	Satellite designation	SAME
WORD 2	Satellite component	SAME
WORD 3	03 UT hours 43 UT minutes 2 UT ten seconds	SAME
WORD 4	0 UT seconds 0045 UT decimal seconds to nearest ten thousandth	SAME
WORD 5	0 billion cycles counted 0 hundred million cyc. ctd. 0 ten million cyc. ctd. 0 million cyc. ctd. 1 hundred thousand cyc. ctd.	SAME
WORD 6	2 ten thousand cyc. ctd. 7 thousand cyc. ctd. 9 hundred cyc. ctd. 7 ten cyc. ctd. 0 unit cyc. ctd.	SAME
WORD 7	0 billion cycles per sec.	Exponent of counter freq. (8 indicates freq. of 10^8 cps)
	0 hundred million cps	Sign of temp. (0 = +,1 = -)
	0 ten million cps	hundred degrees temp. (°F)
	9 million cps	ten degrees temp.
	9 hundred thousand cps	unit degrees temp.

Figure 4.5. SAO Laser Received Teletype Format.

WORD 8	9 ten thousand cps	unused
	7 thousand cps	ten inches Hg (Bar.Pressure)
	4 hundred cps	unit inches Hg
	7 ten cps	tenths inches Hg
	9 units cps	hundredths inches Hg
WORD 9	Line sum check	SAME

Figure 4.5. (Cont'd.).

b. Laser observation cards punched in Par. 2, above. The purpose of this program is to compute the range from the reported cycle count and counter frequency. It does this by using the following equation:

$$r = \left(\frac{n}{F_c}\right)\frac{c}{2},$$

where

r = uncorrected range to satellite in megameters,

n = cycle count reported from tracking station,

c = adopted value of speed of light in a vacuum (2.997925×10^2 megameters/second),

F_c = counter frequency in cycles per second. This is reported from the tracking station and is usually 10^8 cps.

4. The output of the LASOBS I Program consists of punched cards that are in the SAO Laser Observation Card Format. This format is acceptable as input to subsequent programs which apply corrections to the raw ranges (see Par. 7), and is shown in Figure 4.6. A listing of the cards is also printed.

5. The cards are then used as input to a reformat program (LASREP) which converts the data to the format required by the GSDS. This format is shown in APPENDIX A.

6. Punched cards in the required format are mailed to the GSDS.

7. Cards from step 4 are used as input to the LASOBS 2 Program which corrects the raw range for tropospheric refraction, propagation delay of the laser pulse, and the

Field	Cols	Description
1	1-7	Satellite identification
	1-2	year of launch from 1900
	3-5	number of launch in that year
	6-7	particle number Satellite 1959 α 1, for example, would be designated 5900101.
2	8-12	Observation number - each observation of a satellite in a given year is designated by a different number. A numbering scheme aids in identifying different sources of observations. 25000-29999 Uncorrected laser 70000-79999 Baker-Nunn, precisely reduced and corrected laser
3	13	Blank
4	14-17	Station number - in the COSPAR numbering format. Station designations from 7901-7999 are laser sites. Ex. 7901 is station 1, Organ Pass, N. Mex.
5	18-23	Date of observation
	18-19	year, from 1900
	20-21	month
	22-23	day
6	24-33	Time designation - different types of observations have different time systems, which are not based on local time. The systems for each type are as follows: a. Uncorrected Laser - WWV emitted at transmission of laser pulse. b. Corrected laser - A.S. at reception of laser pulse. Note: A.S. is a time scale, adopted by the time-reduction section, for reducing times on the system WWV emitted to times on a system close to that of A.1. The values of the differences (A.S. - WWV emitted) are available in tabular form.

Figure 4.6. SAO Laser Observation Card Format.

Field	Cols	Description
	24-25	hour
	26-27	minute
	28-29	second
	30-33	fraction of seconds, to 0.1 millisecond
7	34-52	The interpretation of the following field depends on the code in column 56. For either type of laser observation column 56 is a 6 and the observation is range.
	34	blank
	35-43	in megameters (decimal point implied before column 37 allows range observations to be specified to 10^{-7} megameter or a tenth of a meter)
	44-47	sign of temperature, temperature in degrees Fahrenheit--uncorrected obs cards only
	48	blank
	49-52	barometric pressure--to hundredths of inches of mercury, uncorrected obs cards only
8	53-58	Index codes
	53	time-precision index

Code no.	Standard error in timing σ_t
1	$\sigma_t \leq 0.0003$ sec

	54-55	Standard deviation of the range, σ_r, in meters and tenths of meters
	56	observation type index

Code	Explanation
6	range (megameters)

	57	blank
	58	Instrument description index (*See Note)

*NOTE: On all laser observations prior to September 1, 1967 this column is blank. After September 1, 1967 all laser observations will contain an 8 in this column.

Figure 4.6. (Cont'd.).

Field	Cols	Description		
		Code no.	Optical observations	Electronic observations
		8	Stationary telescope or camera with focal length greater than 10 inches, photographic	laser
9	59-64	Blank		
10	65-70	Conversion from the UT1 to the A.1 time system, i.e., A.1 - UT1		
	65	minus if A.1 - UT1 is negative, or tens digit if positive and necessary		
	66	units digit of A.1 - UT1 in seconds		
	67-70	decimal fraction A.1 - UT 1		
11	71-80	Identification information		
	71-75	blank		
	76	contains an S if observation is simultaneous		
12	77-78	Blank		
13	79-80	Blank		

Figure 4.6. (Cont'd.).

difference between A.S. and UT1 time. A.S. time is used by SAO to approximate A.T. 1 time, the corrections for which are not immediately available. This time system deviates from Atomic Time by less than 1 millisecond. These corrections are listed in Section 4.222. The program also computes the altitude and azimuth of the satellite for each observation. The output of this program is then used for orbit improvement determinations within SAO. No data which is processed by this program is submitted to the GSDS.

4.22 <u>Corrections to Data</u>

4.221 The following corrections are applied to SAO Laser data during preprocessing:

1. Laser System Delay

The laser contains a firing delay of from 0 to 4 milliseconds from the time of the triggering pulse. This is due to the Q switching mechanism at the rear of the ruby rod which actually causes the laser transmission. The Q switch consists of a rotating prism which is run by a DC motor, therefore no synchronization can be made with the triggering pulse. The time for one revolution of the prism, and therefore the maximum firing delay, is 4 milliseconds. An additional counter is used to time the firing delay for each pulse. This delay is then added to the even second from which the pulse was initiated.

The actual delay time could total more than 4 milliseconds due to other delays in the equipment. All known delays are included with the firing delay in making the correction to the epoch transmission time. The correction is then

$$t \text{ epoch} = t \text{ measured} + t \text{ delay}.$$

This is corrected at the station before transmission via teletype.

2. Zero Set Correction

A zero set correction is added to the measured round trip transit time of the signal. This time interval correction is due to the pulse delay in the electronics and the photomultiplier tube and is determined by calibrating the laser over a known test range once a month or when a component of the equipment is changed. The test range consists of a 1619.5 meter round trip distance for which the standard transit time is 5.40 microseconds. A typical zero set correction is about .2 microseconds which is corrected at the station.

3. Correction to WWV Emitted Time Signal

There is no mathematical correction applied for WWV propagation delay. There is an initial synchronization with WWV emitted by means of a portable clock. The oscillator of the station clock is then set to the portable clock and is kept to within ± 100 microseconds of the portable clock. The allowable error for the variation of station time from WWV emitted is then ± 100 microseconds.

4.222 The following corrections remain to be applied to the SAO Laser data in the GSDS (the numerical values listed are those used by SAO in the LASOBS 2 Program to get the corrected range to the satellite):

1. Atmospheric Correction

This correction is made to account for the effect of the earth's atmosphere on the velocity of light. The following correction should be subtracted from the raw range observed from the New Mexico site:

$$\Delta r = \frac{2.10}{\sin\alpha} \text{ meters,}$$

where

Δr = atmospheric correction to be subtracted from observed range,

α = elevation angle of the observation.

This correction assumes that the index of refraction has a standard exponential variation with height above the earth's surface.

For observations made after 1 January 1968 a new correction has been recommended [Lehr, 1967]. The following correction should also be subtracted from the observed range:

$$\Delta r = \frac{2.238 + 0.0414\ PT^{-1} - 0.238\ h_s}{\sin\alpha + 10^{-3}\cot\alpha} \text{ meters,}$$

where

P = atmospheric pressure, in millibars,

T = temperature, in degrees Kelvin,

h_s = laser's elevation above mean sea level, in km,

α = elevation angle of satellite.

This formula is valid for apparent elevation angles greater than five degrees.

2. Relative Displacement Correction

Since the SAO Laser has been used in conjunction with the Baker Nunn camera at the tracking station, a displacement correction must be used when referring the laser range to a corresponding camera direction. The coordinates of the Organ Pass station, defined to be those of the Baker Nunn camera, are the following:

Latitude	+32° 25' 24".71
Longitude (East)	253° 26' 48".28
Height (above ellipsoid)	1601 meters

These values refer to the North American Datum.

The relative displacement correction which is added algebraically to the measured range is [Anderson, et al., 1966]

$$\Delta r = (-29.0 \sin \phi + 10.0 \cos \phi) \cos \alpha - 1.7 \sin \alpha \text{ meters}$$

for observations before $3^h 28^m$ UT, 11 September 1966; and

$$\Delta r = (15.87 \sin \phi - 2.80 \cos \phi) \cos \alpha - 0.57 \sin \alpha \text{ meters}$$

for observations on or after the above time;

where

ϕ = azimuth angle of the observation,

α = elevation angle of the observation.

The above corrections are for the New Mexico site only (site was closed on June 30, 1967).

3. Time Correction

The reported observation time, t_o, is the time when the laser pulse was transmitted. To get the time the pulse left the satellite, t_1, use

$$t_1 = t_o + \frac{n}{2F_c},$$

where

n = reported cycle count,

F_c = counter frequency in cycles per second.

To obtain the time the laser pulse was received at the station, t_2, use

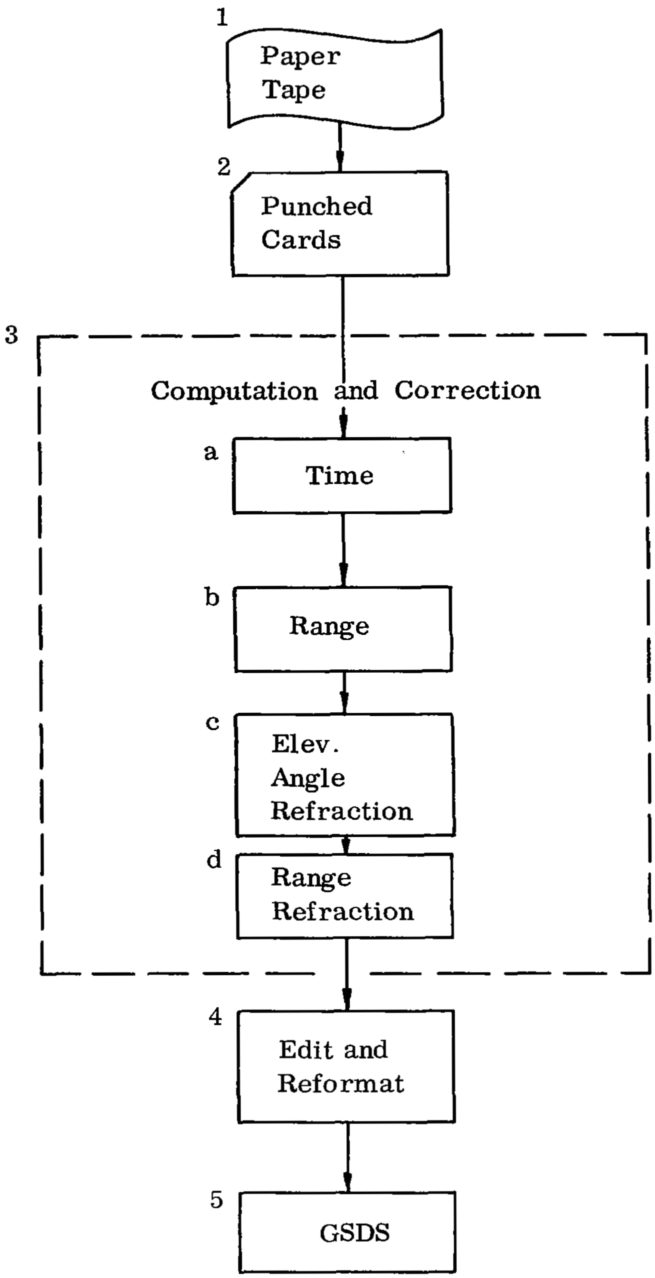
$$t_2 = t_o + \frac{n}{F_c},$$

The time t_2 corresponds to the time of the Baker Nunn camera observation. All the above times are referenced to the A.S. time system.

4.3 GSFC LASER DATA PROCESSING SYSTEM

4.31 Preprocessing Procedures

Ranging data from the GSFC Laser which is deposited in the GSDS was observed at Rosman, North Carolina, and Greenbelt, Maryland, and processed at Greenbelt, Maryland. Figure 4.7 depicts a flow diagram of the preprocessing procedures from time of receipt until the data is deposited in the GSDS. The following is a description of the



Note: Numbers in above figure correspond to numbers of descriptive paragraphs in Section 4.31.

Figure 4.7. GSFC Laser Preprocessing Procedures.

flow-diagram:

1. Data is received from the tracking station via teletype in the form of punched paper tape. No corrections are applied to the data at the tracking station prior to transmission.

2. Upon receipt, the paper tape is run on a IBM 047 keypunch which converts the data to punched cards with no change in format. The format of the punched cards is shown in Figure 4.8.

3. The punched cards are used as input to a Univac 1108 computer which accomplishes the following functions:

a) Computes the time of observation which is defined as the time when the laser pulse was at the satellite. This is done by adding one-half the transit time of the laser pulse to the time of laser firing; however, corrections must be applied for system zero set bias and firing delay. The detailed computation is described in Section 4.321.

b) Computes the range to the satellite. This is done by the following formula:

$$R = \frac{C}{2} (T_R - T_D),$$

where

R = raw range to the satellite,

C = adopted value of speed of light in a vacuum (2.997925×10^8 meters/second),

Column	Description	Example
1-6	Station Name	ROSLAS
7-10	Spacer	.00.
11-15	Satellite Identification	65891
16-18	Day of Year from Jan 0	281
19		.
20-25	Time of Laser Energizing; hour, minute, second (always even second)	104152
26	Spacer	.
27-32	Azimuth in Degrees (to nearest thousandth)	269656
33	Spacer	.
34-38	Elevation in Degrees (to nearest thousandth)	67142
39	Spacer	.
40-42	Delay time between energizing of laser and time at which laser pulse leaves tracker; in tenths of milliseconds	023 (read .0023 sec.)
43-51	Round trip time of laser pulse from transmitter to satellite to receiver; in nanoseconds	008521440 (read .008521440 seconds)
52-57	Spacers	000000
58-80	Blank	

Figure 4.8. GSFC Laser Punched Card Format.

T_R = round trip time interval of laser pulse. This is found in columns 43-51 of received data. It is measured by counting N cycles of a 100 Mc. counter. Therefore $T_R = \frac{N}{10^8}$ sec.,

T_D = system zero set bias = 90 nanoseconds.

c) The measured elevation angle is corrected for refraction as shown in Section 4.321.

d) The computed range is corrected for refraction as shown in Section 4.321.

4. After the corrections mentioned in Paragraph 3 are applied to the data; a short arc, single station orbital fit, is made to the range; azimuth; and elevation data. This process consists of an iterative least squares adjustment using the orbital parameters as the initially estimated quantities. Weights assigned to the measured range, azimuth and elevation are 2 meters, 200 arc-seconds and 100 arc-seconds respectively. Each successive iteration is begun with the most recently corrected orbital elements but with the original weight matrix for the orbital elements.

Convergence is based on the percentage change in the rms of the range residuals in successive iterations. When these change by less than 5 per cent the iteration process is halted. The final residuals are then checked to insure against significant systematic correlation. This is done by a runs test consisting of the following:

For N random residuals (N>25), we can expect the number of sign changes, n, to be a normal distribution with mean

$$\bar{n} = 1/2(N + 1),$$

and standard deviation

$$\sigma = \sqrt{\frac{N(N - 2)}{4(N - 1)}} .$$

The normal deviate, z, can be computed using n_o as the observed number of sign changes;

$$z = \frac{n_o - \bar{n}}{\sigma} .$$

The value z is then checked against tabulated values of the standard normal distribution to test for significant systematic correlation of the residuals.

The data is then edited based on a five sigma rejection criterion where sigma is the rms of an observation. This is computed by

$$\text{rms} = \sqrt{\frac{\Sigma(x_i^o - x_i^c)^2}{n-7}},$$

where

$(x_i^o - x_i^c)$ = difference between observed and computed ranges for the i^{th} data point,

n = number of data points.

If any of the three measurements for a given observation exceeds five sigma, all measurements for that observation are rejected.

The acceptable data points are then reformatted into the required GSDS format. This format is shown in

5. The program output consists of magnetic tape containing the properly formatted data. The magnetic tape is then submitted to the Geodetic Satellites Data Service.

4.32 Corrections to Data

4.321 The following corrections are applied to GSFC Laser data during preprocessing.

1. Observation Time Correction

To find the actual time of observation, i.e., the time when the laser pulse left the satellite, we must first find the actual time of firing of the laser by the following formula:

$$T_F = T + \Delta t + T_W,$$

where

T_F = actual firing time of laser,

T = time of initiation of laser energizing pulse, and is found in columns 20-25 of received data,

Δt = delay from time T to actual firing time of laser, which is found in columns 40-42 of received data,

T_W = propagation delay time from WWV. This has the value for Rosman of 3.6 milliseconds before 12/1/66, and 7.63 milliseconds on or after 12/1/66.

WWV is not used for time synchronization at the Greenbelt, Maryland, station. Time synchronization is maintained with the GSFC time standard and is accurate to ± 5 microseconds.

The time of observation can then be found by adding one-half the round trip time interval to the time of actual laser firing. The reported round trip interval, however, is too long by an amount equal to the system delay. The formula for time of observation is

$$T_O = T_F + 1/2\ (T_R - T_D),$$

where

T_O = time laser pulse was at satellite (this is the observation time reported to the GSDS),

T_F = actual firing time of laser,

T_R = round trip time interval of laser pulse, and is found in columns 43-51 of received data,

T_D = total delay in signal due to telescope optical path length and delay through photomultiplier tube.

The value for T_D is currently 90 nanoseconds and is measured over a precisely calibrated range before and after each pass.

2. Atmospheric Refraction Corrections

Since the range is calculated by using the speed of light in a vacuum, a correction must be made for the effect of the atmosphere, which increases the optical path from station to satellite. A correction is first applied to the measured elevation angle according to the following formula [Moss, 1967]:

$$E_o = E_m - \frac{.002919}{\tan E_m} \text{ radians,}$$

where

E_o = elevation angle of observation corrected for refraction,

E_m = measured elevation angle. This value is obtained from columns 34-38 of received data.

A refraction correction is then applied to the computed range by the following formula [Moss and Wells, 1967]:

$$\Delta r = \frac{2.1}{\sin E_o} \text{ meters,}$$

where

Δr = refraction correction to be subtracted from computed range,

E_o = corrected elevation angle.

4.322 No corrections remain to be applied to GSFC Laser data presently in the GSDS [Moss, 1967].

4.4 DISCUSSION

Laser data presently in the GSDS consists of unsmoothed data from both the SAO and GSFC systems. The data was taken at different periods of time and consists of the following:

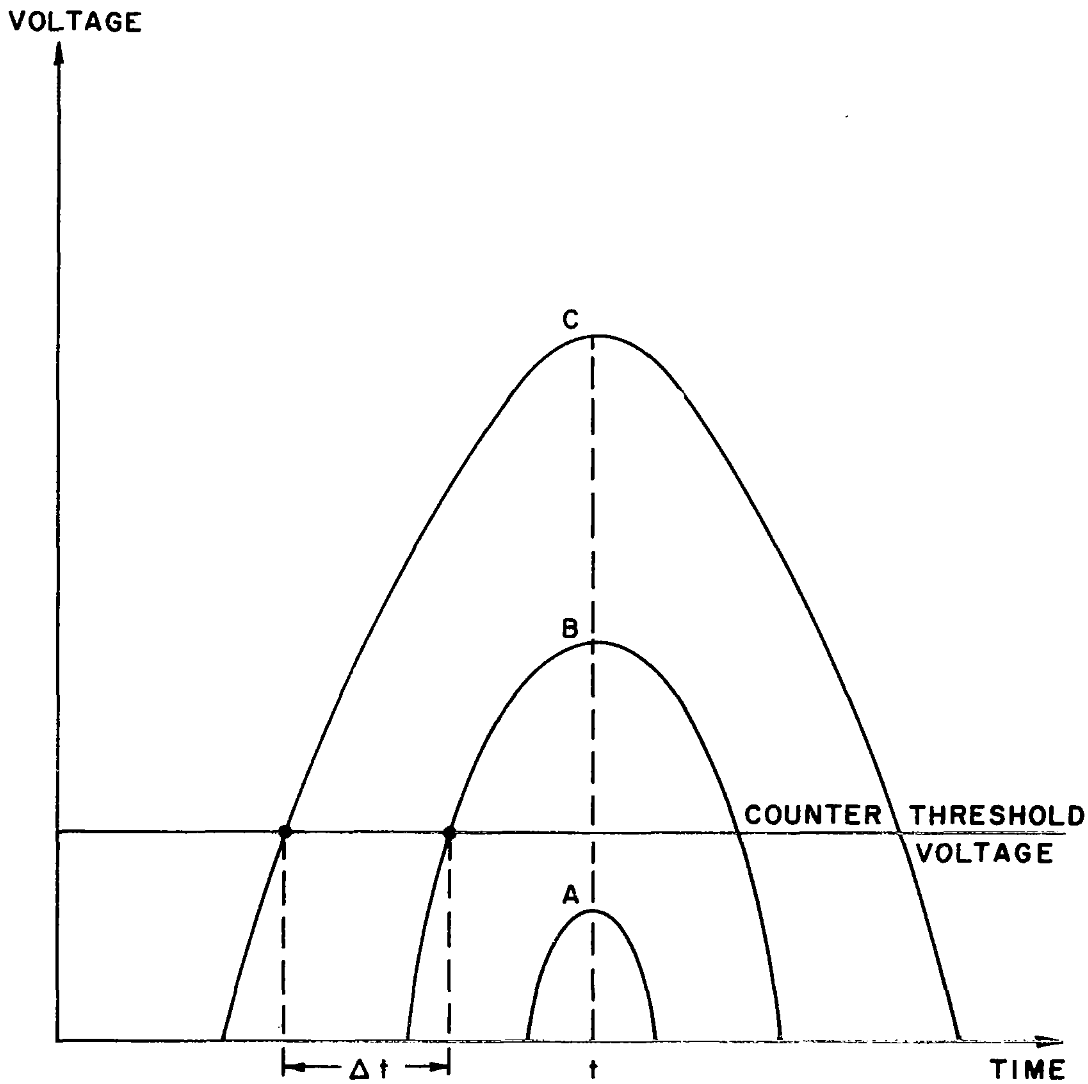
a. SAO data is that observed from GEOS A only, through October 1966, although data from all observed satellites will be deposited shortly.

b. GSFC data consists of that observed from all five satellites carrying retroreflectors. GEOS A data was taken in the fall of 1966 and in May, 1967. The May, 1967 data was tracked from Greenbelt, Maryland; all other data being observed at Rosman.

There is an uncorrected systematic error remaining in the laser data from both systems which is due to the fact that the measured time interval is dependent on the received signal strength. This is because the threshold voltage for stopping the time interval counter is fixed but the amplitude of the pulse varies with the received signal strength. A strong signal stops the counter at a lower point on its leading edge and produces a smaller value of the measured time interval. This error should be less than one meter and therefore does not significantly affect the accuracy of the measurement. Figure 4.9 depicts this error graphically.

There are no error models currently used by either organization. Investigations have indicated [Moss and Wells, 1967] that systematic errors such as constant bias, rate bias, and time bias may be effectively masked by the short arc, single-station orbital fit which is used in the GSFC Laser preprocessing.

Another application of the laser in satellite geodesy is currently being tested at the Air Force Cambridge Research Laboratories in Bedford, Mass. The laser used is similar to those previously described and is operated in conjunction with a PC-1000 geodetic stellar camera which photographs the reflected pulse at the satellite. This operation would yield both range and direction from



Received pulse A is too weak to stop the time interval counter.

Although pulses B and C reach their maximum aplitude at the same time, t, the stronger pulse stops the time interval counter at an earlier time.

Figure 4.9. Measured Time Interval Vs. Received Signal Strength.

one observation. No data from this experiment is currently in the GSDS.

As can be seen from APPENDIX A, there is no specification for SAO Laser data in the GSDS required format. In spite of this, cards submitted to the GSDS from SAO have a 13 punched in columns 60-61, and a 65 punched in columns 62-63. These numbers serve as identification codes for SAO Laser data.

Experimentation with a continuous wave gaseous laser is being conducted at Goddard Space Flight Center. This CW system will be tested on the GEOS B satellite and will be used to determine whether laser beams transmitted to the satellite arrive at predicted power levels. The ground transmitter will be a CW argon laser Doppler experiment transmitter. The detector will consist of an optical system, optical filter, photo multiplier, and processing electronics.

5. U.S. NAVY DOPPLER TRACKING NETWORK

5.1 GENERAL SYSTEM DESCRIPTION

5.11 Introduction

The U.S. Navy Doppler Tracking Network (TRANET) is a system of radio receiving stations used for acquiring and processing data from near earth satellites for use in geodetic and geophysical research. The quantity measured by a TRANET tracking station is the Doppler frequency as a function of time. The TRANET system has been in operation since 1959 and is operated by the New Mexico State University for the Department of the Navy, under the technical direction of The Applied Physics Laboratory of The Johns Hopkins University.

There is also a Doppler tracking network operated by the Naval Astronautics Group at Point Mugu, California. It is operated independently of the TRANET system and has the mission of providing Doppler and other data necessary for the operation of the Navy Navigational Satellite System. This system will not be discussed further.

5.12 Principles of Operation

The system concept derives from the fact that while a satellite transmitter sends a continuous, unmodulated wave at a fixed frequency, the received signal at the tracking station exhibits a shift in frequency due to the relative velocity of the satellite and observing station. This received frequency is a function of the transmitted frequency, velocity of propagation, and the rate of change of the slant range between the satellite and station. As shown in [Guier and Weiffenbach, 1958], from observations at one station the satellite period, time and distance of its closest approach, and its relative velocity can be determined. If observations are made from three or more known stations, the orbital parameters may be deduced.

The Doppler signal is determined generally in the following manner. The received signal is compared to a reference frequency to determine a frequency shift

$$f_c = f_o - f_r,$$

where

f_c = difference, or beat, frequency,

f_o = reference frequency derived from the local oscillator,

f_r = received frequency from the satellite.

The received frequency is composed of the following elements:

$$f_r = f_s + f_D + f_I,$$

where

f_s = frequency transmitted by the satellite,

f_D = Doppler frequency shift in received signal,

f_I = error frequency due to refraction.

Combining the two equations, we get for the Doppler frequency:

$$f_D = (f_o - f_s) - f_c - f_I.$$

The $(f_o - f_s)$ term is a deliberate satellite frequency offset and is considered constant for a satellite pass.

In order to obtain an accurate measurement of time and frequency, the ground station must have a stable reference frequency and time standards to determine clock rate and clock epoch. TRANET stations employ standard frequency VLF transmissions in order to determine frequency, which is accurate to approximately one part in 10^{10}. Clocks carried by some satellites are used for station clock epoch control. Portable clocks are also used, and station clocks are synchronized by these methods to within approximately .2 milliseconds. Standard time broadcasts from WWV and other stations are used only as backup for epoch control.

The primary time standard in the TRANET system is that of the U.S. Naval Observatory. This is used to monitor the working standard for the TRANET system, which is located at the Applied Physics Laboratory, Howard County, Maryland. The working standard monitors satellite clocks used in other programs. The monitoring results are made known to the tracking stations which can then use the satellite timing signals for epoch control.

The operation of a ground tracking station is depicted schematically in Figure 5.1. The signals from the satellite are transmitted on two frequencies, f_s, which are coherent and related by simple ratios. Two frequencies are used to facilitate the removal of refraction effects (see Section 5.221), and both undergo the same operations at the receiving station. The frequencies, f_r, are received at the ground station and are compared with station reference frequencies, f_o. This gives two beat frequencies, f_c, in the range of tens of kilocycles. During a pass of the satellite, the Doppler frequency takes on the values above and below the reference frequency. Since the sign of the beat frequency cannot be determined, the satellite frequency is offset deliberately from the station frequency by an amount $(f_o - f_s)$ greater than the largest Doppler shift in order to prevent the beat frequency from passing through zero. The offset is usually 35 or more parts per million, since the maximum Doppler shift is about 25 parts per million. The beat frequency is produced in the receiver detector and is the frequency tracked in the phase lock tracking loop.

The respective beat frequencies then enter a tracking filter, a narrow pass filter with a band width of about

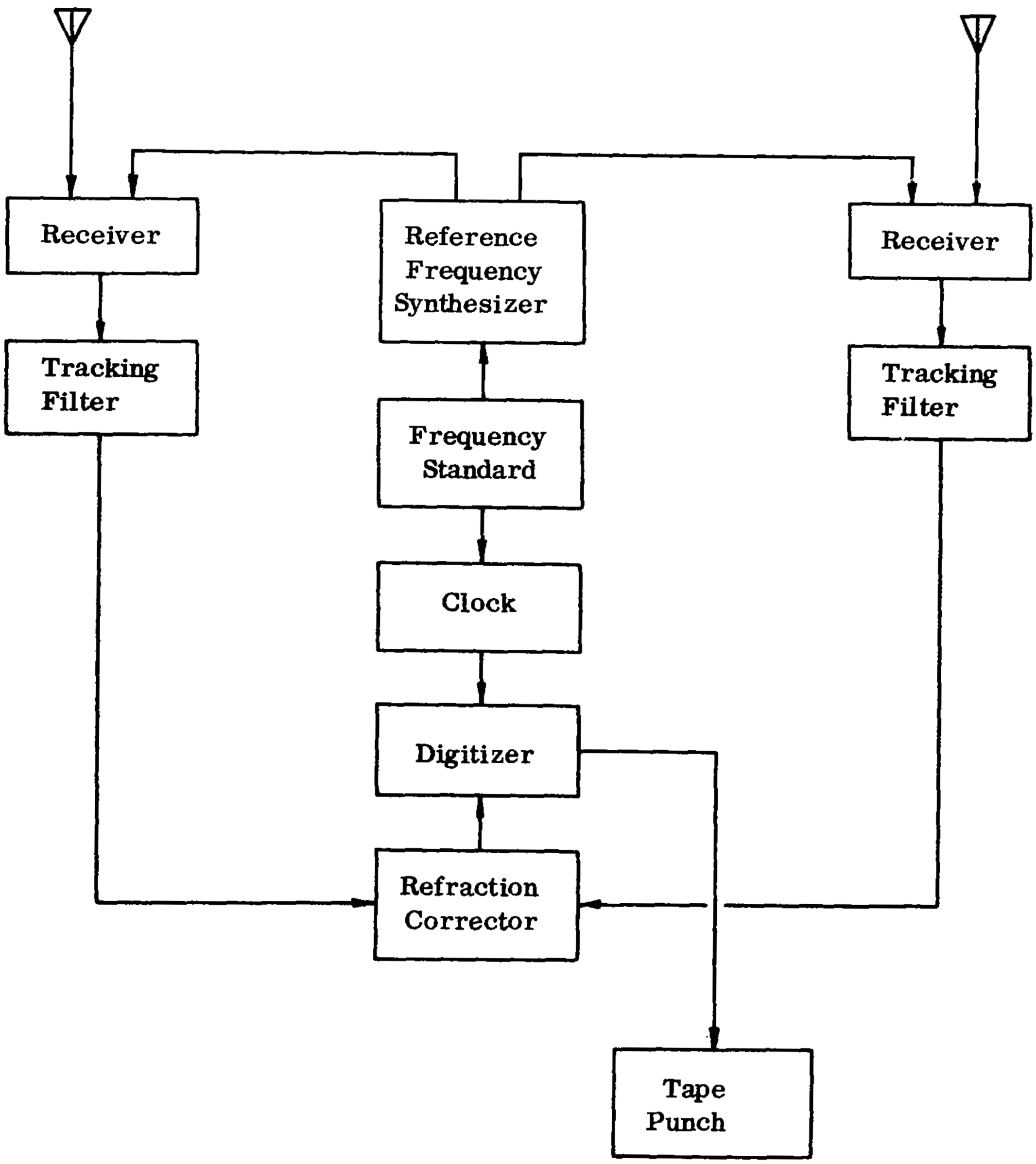


Figure 5.1. Block Diagram of TRANET Receiving Station.

10 cycles, whose center frequency automatically adjusts itself to the input frequency. This allows reception of a changing frequency in a band width that is very narrow, in order to give a favorable signal to noise ratio.

The outputs of the tracking filters then enter the ionospheric refraction correction unit. This unit combines the two signals by analog means to eliminate, to first order, the refractive effects of the ionosphere. See Section 5.221 for the specific method of correction. The output beat frequency (effective frequency) can now be given as

$$f_e = (f_o - f_s) - f_D = \Delta f_s - f_D.$$

The corrected output of the refraction unit is now digitized, with a sample of the effective frequency usually taken every four seconds, although it may be taken every 2^m seconds, where m is any positive integer. The digitizer counts a preset number of cycles, n_c, of the effective frequency and determines the time in tenths of microseconds required for the count. The value n_c is chosen by the tracking station operator prior to each pass. The time interval begins at the first positive direction zero crossing of the Doppler signal after an integral second. The time interval ends at the $n_c{}^{th}$ positive zero crossing. The metering frequency is 5 Mc. and provides a resolution of .2 microseconds. Since the metering frequency has an accurately known period, the period counter provides an accurate measure of the duration of n_c cycles. The preset count is variable, and is chosen to make the time interval just under one second at the beginning of a pass, when the effective frequency is lowest.

The digitizer output for each point consists of the integer second at which the counting process is initiated, and the time interval of the count, T. The quantity n_c/T then represents the effective frequency f_e.

The time of the observation, t_o, is determined during preprocessing by adding one-half the measured time interval, T, to the epoch of the beginning of the measurement. Although the measurement is supposedly of the instantaneous frequency, it is actually the average value of the frequency over an interval so short that there is negligible error involved in considering the measurement as the true frequency value at the center of the time interval.

TRANET stations may track satellites operated by the Navy Navigational Satellite System, a few of which transmit time signals at two-minute intervals. When a timing word is recognized in the data, a pulse is produced, which causes the digitizer to punch a time data point on the paper tape, in place of the regular time interval information. The tape is then ready for preprocessing.

5.13 TRANET System Operations

Figure 5.2 shows schematically the operation of the Navy Doppler Tracking Network. The tracking stations,

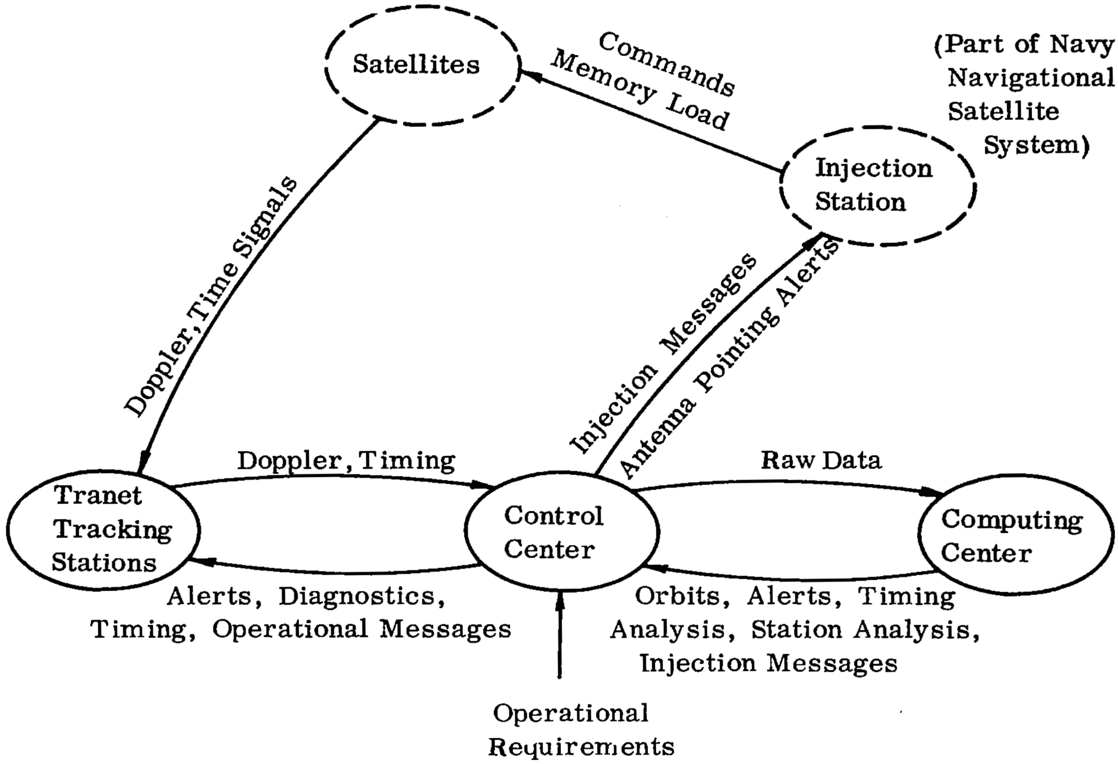


Figure 5.2. Functional Diagram of the TRANET System.

after receiving a satellite alert, receive the Doppler and time data. The data, along with optional weather data and narratives, are transmitted via teletype to the Control Center. After logging and transferral to magnetic tape, the data is sent to the Computing Center for processing. Operational information, station diagnostics, and various other reports are transmitted from the Control Center to the stations.

The following is a brief description of the four major components of the TRANET System.

a. Satellites--There are no satellites under the operational control of the TRANET system. The satellites used are from other programs and transmit two or more frequencies controlled by the same highly stable oscillator. Since the inception of the system, several frequencies have been used; always in pairs with simple ratios (1:2, 3:8, and so forth). A list of satellites which have carried Doppler instrumentation is given in TABLE 8.

b. Tracking Stations--The tracking stations carry out measurements as described in the previous section. Stations may be either permanent or mobile. There are currently thirteen permanent and four mobile stations in the system, whose characteristics are shown in TABLE 9. One type of station, known as a Tracking Filter station, uses equipment which phase locks to the satellite signal after the signal has been heterodyned down to the 10 to

TABLE 8

SATELLITES WITH DOPPLER INSTRUMENTATION

Name	Desig-nation	Transmitted Frequencies	Launch Date	Ceased Transmitting
I-B	1960 γ 2	B,C	13 Apr 60	11 Jul 60
II-A	1960 η 1	B,C	22 Jun 60	26 Oct 62
III-B	1961 η 1	B,C	22 Feb 61	1 Apr 61
IV-A	1961 o 1	C,Z	29 Jun 61	
IV-B	1961 α η 1	C,Z	15 Nov 61	2 Aug 62
TRAAC	1961 α η 2	C	15 Nov 61	12 Aug 62
ANNA I-B	1962 β μ 1	B,C	31 Oct 62	
5A1	1962 β ψ 1	Z	19 Dec 62	19 Dec 62
5A3	1963-22A	Z	16 Jun 63	
5BN-1	1963-38B	Z	28 Sep 63	22 Dec 63
5E-1	1963-38C	Y	28 Sep 63	
5BN-2	1963-49B	Z	5 Dec 63	
5E-3	1963-49C	C,Y,X	5 Dec 63	9 Mar 64
5C-1	1964-26A	Z	3 Jun 64	23 Aug 65
OSCAR 01	1964-63A	Z	6 Oct 64	8 Oct 64
BE-B	1964-64A	Y	9 Oct 64	
OSCAR 02	1964-83D	Z	12 Dec 64	31 Dec 64
5E-5	1964-83C	Y	12 Dec 64	
OSCAR 03	1965-17A	Z	11 Mar 65	6 Apr 65
BE-C	1965-32A	Y	29 Apr 65	
OSCAR 04	1965-48C	Z	24 Jun 65	
OSCAR 05	1965-65F	Z	13 Aug 65	
GEOS-A	1965-89A	Y	6 Nov 65	
OSCAR 06	1965-109A	Z	22 Dec 65	
OSCAR 07	1966-05A	Z	28 Jan 66	
OSCAR 08	1966-024A	Z	25 Mar 66	
OSCAR 09	1966-41A	Z	19 May 66	
OSCAR 10	1966-76A	Z	18 Aug 66	
D1A	1966-13A	Z	17 Feb 66	
D1C	1967-11D	Z	8 Feb 67	
D1D	1967-14A	Z	15 Feb 67	
OSCAR 12	1967-34A	Z	14 Apr 67	
OSCAR 13	1967-48A	Z	18 May 67	
OSCAR 14	1967-92A	Z	25 Sep 67	
GEOS B	1968-02A	T	11 Jan 68	

NOTE:

B = 162,216 MHz.
C = 54,324 MHz.
Z = 150,400 MHz.

T = 162,324,972 MHz.
Y = 162,324 MHz.
X = 648 MHz.

TABLE 9

CHARACTERISTICS OF TRANET STATIONS

STATION LOCATION Fixed Stations	TYPE	FREQUENCY STANDARD	STATION CLOCK REFERENCES Epoch	Clock Rate	Current Clock Errors (msec.)
008 - Brazil	NACODE	Hermes 105	Sat.	NPG/NLK	.1
013 - Japan	NACODE	Hermes 105	Sat.	NPG/NLK	.2
014 - Alaska	Tracking Filter	Sulzer 2.5	Sat.	NPG/NLK	.2
018 - Thule	NACODE	Hermes 105	Sat.	NPG/NLK	.1
100 - Hawaii	NACODE	Hermes 105	Sat.	WWVL	.1
103 - Las Cruces	NACODE	Sulzer 2.5	Sat.	NPG/NLK	.1
106 - England	Tracking Filter	Sulzer 2.5	MSF	GBR/GBZ	.2
111 - Howard County	" "	Sulzer 2.5	Nav.Obs.	APL Stds.Lab.	.1
112 - Australia	NACODE	Hermes 105	Sat.	NPG/NLK	.2
115 - S. Africa	NACODE	Sulzer 2.5	Sat.	GBR/GBZ	.1
117 - Samoa	NACODE	Hermes 105	Sat.	NPG/NPM	.1
121 - Philippines	NACODE	Hermes 105	Sat.	NPG/NLK	.2
717 - Seychelles (Van 306)	Tracking Filter	Sulzer 2.5	Sat.	GBR/GBZ	.2
Van Stations					
307	Tracking Filter	Sulzer 2.5	Sat.	(VLF)	
311	Tracking Filter	Sulzer 2.5	Sat.	(VLF)	
312	Tracking Filter	Sulzer 2.5	Sat.	(VLF)	
314	Tracking Filter	Sulzer 2.5	Sat.	(VLF)	

50 Kc. range. Another type of station equipment, known as NACODE, phase locks to the satellite signal in the RF region.

There is a Doppler tracking station supported by the National Science Foundation located at McMurdo Sound, Antarctica. While not a part of the TRANET system, this station cooperates closely with it.

c. Control Center--The control center is the hub of the system, and is linked to each station by teletype. The control center is located at the Applied Physics Laboratory, in Howard County, Maryland.

d. Computing Center--The computing center receives data from the control center and processes it as described in Section 5.21. The computing center is located in Dahlgren, Virginia.

The system provides a high density of data for satellites in any inclination. The basic precision in satellite position measurements for orbital heights of 1000 km is about 10 meters for Doppler data gathered during a single pass. The system provides approximately fifty passes per day for each satellite that is being tracked. A typical pass may contain 200 or more data points. Data attrition from all causes (transmission errors, malfunctions, lost passes) is usually below ten percent.

5.14 The GEOCEIVER

The preceding sections have described the equipment currently in use to measure the instantaneous Doppler frequency from geodetic satellites. A new, man-portable geodetic receiver is being developed by The Applied Physics Laboratory of The Johns Hopkins University. The GEOCEIVER differs from present TRANET station equipment in the following respects:

a) GEOCEIVER employs an integrated Doppler counting technique, in which a measure of the change in slant range to the satellite is obtained by counting the number of Doppler cycles received between successive one-minute markers.

b) GEOCEIVER is much smaller and lighter than current TRANET station equipment.

c) The data format results in a fifteen to one reduction in the number of data points from a pass. This is because the GEOCEIVER period count is 60 seconds; whereas TRANET stations record a measurement every four seconds.

d) Time epoch is obtained automatically from clock-carrying satellites during tracking.

e) GEOCEIVER is adaptable to a semi-automatic mode of operation.

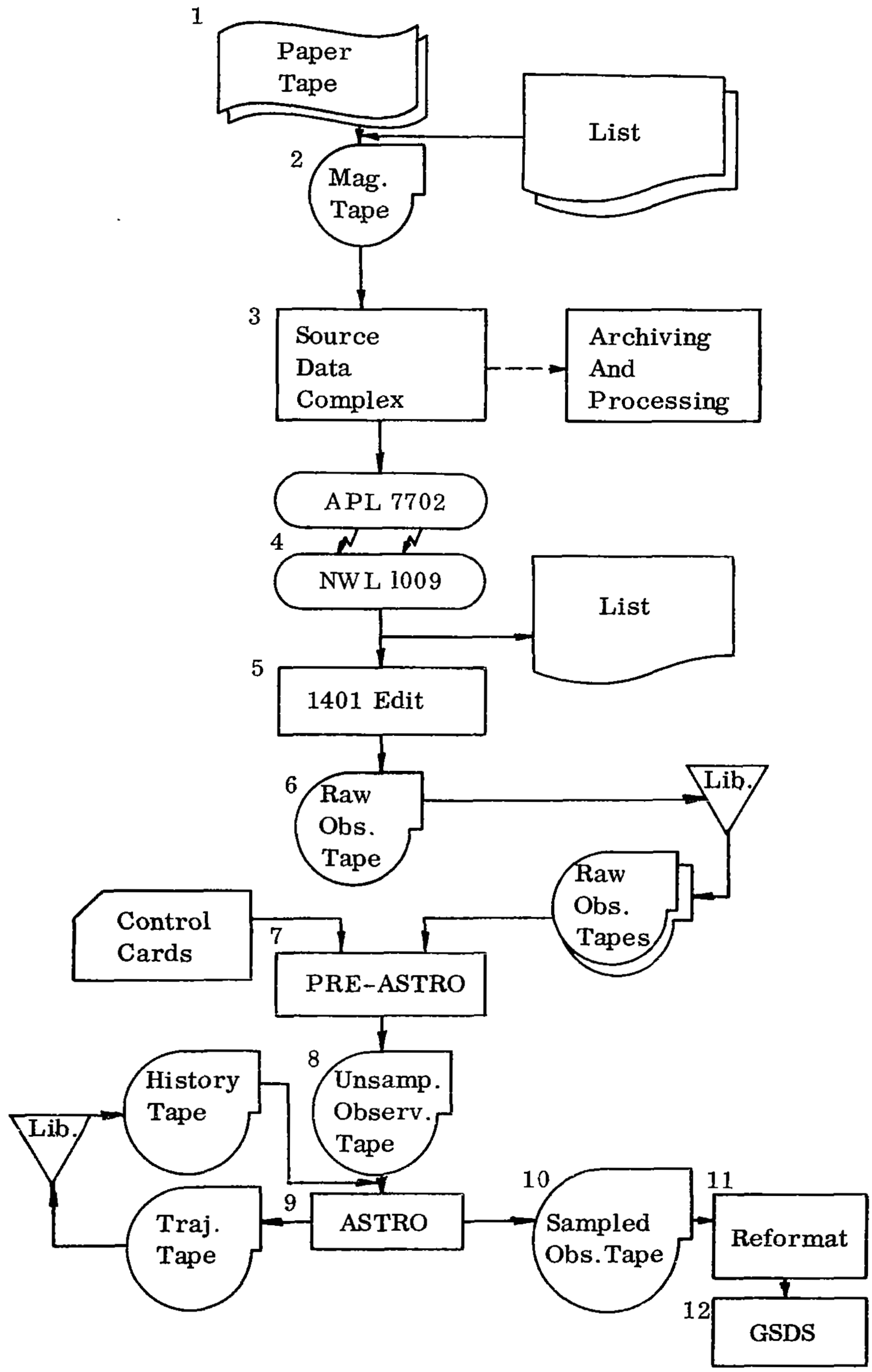
The method of measuring the time integral of the Doppler frequency can be briefly described as follows. After the received signal enters a phase locked receiver, a phase comparator measures the difference in phase between the received signal and the local oscillator, and controls the local oscillator frequency so that the difference is driven toward zero. A counter counts the total number of cycles of the beat frequency. The counter starts at zero when the first time signal arrives from the satellite after coming over the horizon. Each succeeding one-minute time interval causes the contents of the counter to be read out, without destroying its contents. Therefore, the counter always contains the total number of cycles since the first time signal. The difference between two successive counter readings gives the integral of the Doppler frequency over the one minute interval between timing signals, measured in the proper time frame of the satellite.

Since the GEOCEIVER has yet to be employed operationally, it will not be dealt with further. For additional information, see [Stansell, 1965].

5.2 TRANET DOPPLER DATA PROCESSING SYSTEM

5.21 Preprocessing Procedures

All Doppler data from the U.S. Navy TRANET System is initially processed by the Applied Physics Laboratory (APL) of Johns Hopkins University. It is also processed at the Naval Weapons Laboratory (NWL), Dahlgren, Virginia. Figure 5.3 depicts a flow-diagram of the preprocessing steps from time of receipt from the tracking station to storage at the Geodetic Satellites Data Service. The following is a description of the flow diagram.



Note: Numbers in figure correspond to numbers of descriptive paragraphs in Section 5.21.

Figure 5.3. TRANET Doppler Preprocessing Procedures.

1. Data is received at the APL Control Center from the tracking stations via teletype in the form of five-level teletype code punched paper tape. The tape contains a message consisting of three parts:

a. The header contains digits coded to identify and calibrate the accompanying data.

b. The data section contains 11-digit data points, each representing one Doppler time interval reading and its associated time of observation. Timing points may intermittently replace a data point in this section.

c. The ending consists of a data terminator, a weather message, an optional narrative, and a message terminator. The format of the received paper tape printout is shown in Figure 5.4. The data is corrected for first order ionospheric refraction at the tracking station prior to transmission via teletype (see Section 5.221).

2. The paper tape data for each pass is reproduced in the same format onto a single magnetic tape. This tape accumulates data for all passes tracked by all stations during a 24 hour period. The tape is then delivered to the APL Computing Center for processing.

3. The magnetic tape is used as input to a "Source Data Complex" program on an IBM 1410 computer. This program checks the raw data for correctness of header and of data format. It also separates the timing points from the data message. For each data point in the data section

HEADER (3 repetitive lines to avoid error)	"382-03164.65.153.0139.261&0000&00140.06655.13
	"382-03164.65.153.0139.261&0000&00140.06655.13
	"382-03164.65.153.0139.261&0000&00140.06655.13
HEADER TERMINATOR	//
	59769418060
	59809410288
	59849402274
	59889394042
	59929385674
	59969377084
DATA (typically 100 or more points)	60009368252
	60049359210
	60089349898
	62248389496
	62288361438
	62328333064
	62368304324
SATELLITE TIME POINT	62400099370
	62448245828
	67525908308
	67565905140
DATA TERMINATOR	//"382-22222.65.153.0200.071&2400&00000.10190.21
WEATHER MESSAGE (3 repetitive lines)	"382-22222.65.153.0200.071&2400&00000.10190.21
	"382-22222.65.153.0200.071&2400&00000.10190.21
NARRATIVE MESSAGE	FFFF STRONG SCINTILLATION BEFORE OA FFFF
MESSAGE TERMINATOR	//

Figure 5.4. Received Doppler Paper Tape Format.

of the message there are four digits representing the time of observation and seven digits representing the measured time interval to count n_c cycles. One output of the program is the data resulting from the above operations, prepared for transmission to NWL.

Another output consists of a magnetic tape containing all of the data separated by satellite, in chronological order, along with header and weather information. One copy of the tape goes to the APL archives for permanent storage. Further processing of the data at APL for the purpose of preparing operational diagnostic messages is also conducted. The processing consists mainly of data editing, orbital fitting of data, and determining the orbital elements. Since data in the GSDS is not affected by these procedures, they will not be mentioned further.

4. The data from the output of the IBM 1410 is transmitted from APL to NWL by an IBM 7702 via a data phone direct line. The data is received at NWL by an IBM 1009 Data Transmission Unit. The format of the transmitted data is shown in Figure 5.5. A description of the data shown in Figure 5.5 is given in APPENDIX E.

5. The received data is immediately edited and recorded on magnetic tape by the "Anna Copy and Print Program" on an IBM 1401 computer. The edit consists basically of the removal of narrative messages and a check of alpha

```
007 006 63031 261 63 274 123c 30000 00000  -0000   -00092 05550 45•*

  FFFF SIGNALS DURING PASS FAIR            STR TAKEN  FFFF

LØGRCD

007 012 63031 266 63 274 1336 00000 00000  +0251   -00091 20479 26=*

 89649511708 89689505694 89729499390 89769493034 89809486482 19849479830 89889472994 89929466034 899
69458928 90009451682 90049444212 90089436644 90129428882 90169420978 90209412928 90249404636 90289396
6206 90449360740 90489351418 90529341868 90569332172 90689301778 90729291248 90769280518 90809269594
 90849258436 90889247072 90929235488 90969223650 91009211636

 91049199382 91089186874 91129174172 91169161218 91209148020 91249134594 91289120900 91329106976 913
69092788 91409078324 91449063660 91489048778 91529033534 91569018134 91609002440 91648986444 9168897
0180 91728953670 91768936878 91808919872 91848902516 91888884950 91928867100 91968848960 92008830562
 92048811838 92088792934 92128773630 92168754188 92208734426

 92248714356 92288694080 92328673470 92368652592 92408631480 92448610108 92488588472 92528566564 925
68544394 92608522000 92648499318 92688476428 92728453326 92768429952 92808406338 92848382514 9288835
8490 92928334264 92968309808 93008285176 93048260340 93088235354 93128210172 93168184834 93190011366
 93248133706 93288107946 93328082040 93368056042 93408029906

 93448003710 93487977398 93527951064 93567924650 93607898162 93647871654 93687845154 93727818608 937
67792086 93807765550 93847739056 93887712586 93927686186 93967659820 94007633554 94047607364 9408758
1280 94127555290 94167529428 94207503712 94247478126 94287452696 94327427422 94367402320 94390011396
 94447352700 94487328210 94527303898 94567279840 94607255992

 94647232402 94687209032 94727185932 94767163106 94807140502 94847118208 94887096196 94927074506 949
67052940 95007031798 95047010922 95086990264 95126970016 95166950030 95206930320 95246911046 9528689
1804 95326873120 95366854654 95406836504 95446818638 95486801070 95526783872 95566766924 95590011354
 95646733968 95686717934 95726702224 95766686768 95806671608

 95846656756 95886642200 95926627880 95966613882 96006600164 96046586710 96086573440 96126560608 961
66547960 96206535550 96246523410 96286511540 96326499886 96366488520 96406477344 96446466444 9648645
5734 96526445284 96566435066 96606425046 96646415230 96726396280 96886360754 96926352374 96966344160
 97006336116 97046328260 97086320594 97126313054 97166305750

 97206298650 97246291546 97286284652 97326277944 97366271382 97406264954 97446258686 97486252548 975
26246554 97566240694 97606234962 97646229368 97686223902 97726218548 97766213310 97806208204 9784620
3200 97886198312 97926193548 97966188868 98006184330 98046179866 98086175494 98126171256 98166167070
 98206162990 98246159040

LØGRCD
```

Figure 5.5. Format of Data Transmitted to NWL.

characters for obvious transmission errors. Good data is copied in the following sequence:

a) Header--This is edited for blanks in proper places, for correct alpha characters, and for proper length. Narrative messages are discarded.

d) Data--The data points are edited for alpha characters and a blank between adjacent records. If a record (one blank followed by eleven numeric characters) is determined to be bad, a constant (four blanks, one, six blanks, one) is substituted in its place. The good data points remain as received from APL, containing times of observations and the interval required to count a preset number of beats.

c) Logical Record--This is edited for length and for the word LOGRCD. If a bad or missing logical record is found following good data, a logical record is forced on the tape so that the good data may be used.

If bad data are encountered by the program, an identifying mark is printed in the right margin of the line in question.

6. The output of the 1401 edit is a magnetic tape which is placed in the Raw Observation Library for permanent storage. These tapes are used as input, when required, to the Pre Astro Program. Control cards are also used as input. These contain values for the allowable data time gap, the time block for extracting pertinent data and the

satellite offset frequency correction.

7. The PRE-Astro Program is run on the IBM 7030 computer and performs the following functions:

a) Extracts the Doppler observations of a particular satellite from two consecutive Raw Observation tapes, each of which contain data from all observed satellites in chronological order for a 24-hour period. Each PRE-Astro run results in an "Astro Unsampled Observation Tape," which contains observation data from one satellite for a 48-hour period.

b) Detects and eliminates observations containing obvious transmission errors in the numerical data. The edit performed previously by the 1401 program had scanned only alpha characters for transmission error. The PRE-Astro edit consists of checking the data format, and checking for time gaps in the data. If a gap of 1-1/2 minutes occurs, data points from the entire pass are deleted. It also checks the Q pair designation in the header to delete any single frequency data which may have been submitted. The elevation angle for each observation is computed and all data points whose elevation angle is less than 10 degrees are deleted.

c) Computes the observation time and frequency from the received data using the following equations:

$$(1)\quad t_o = t + T/2 + \Delta t_c,$$

where

t_o = corrected time of observation,

t = time at which beat cycle count is initiated (obtained from received data),

T = time required to count n_c beat cycles (obtained from received data),

Δt_c = station clock time error (obtained from header of received data).

$$(2)\quad f_D = \Delta f_s + \Delta f_o - n_c/T,$$

where f_D = Doppler frequency received from satellite, corrected for 1st order ionospheric refraction,

Δf_s = effective satellite oscillator offset frequency $= f_o - f_s$ (obtained from control cards),

Δf_o = frequency standard correction (obtained from header of received data),

n_c = preset number of beat cycles to be counted (obtained from header of received data).

d) Arranges data into the format required by the ASTRO Program and records this on the output magnetic tape.

8. The ASTRO Unsampled Observation Tape contains the edited frequency difference Doppler observation data from one satellite for a 48-hour period. The data is arranged in blocks of two logical records each, a header and a trailer. Each block contains data from one observation station during one satellite pass. The header contains station location and identification data, which includes time of closest approach of the satellite, number of observations, observation epoch, time corrections, and data quality indicators

made in the 1401 edit. The trailer contains the frequency and time of each observation plus a weight corresponding to the degree of scatter of each observation.

9. The ASTRO Computer Program is the primary program in the preprocessing sequence. The program performs a variety of functions, including orbit integration, data filtering, orbit improvement, and data evaluation. The following is a description of the major segments of the program:

a) Input--Program input consists of the ASTRO Unsampled Observation Tape, control cards, and a history tape. The history tape contains the final values of an orbit improvement for the same satellite over the previous two-day period. This has been computed by a prior run of the ASTRO Program.

b) Orbit Integration--The purpose of this program segment is to compute a standard trajectory for each satellite. The computed trajectory may then be used as a reference for filtering observation data. This is done by integrating standard satellite orbit equations twice. The first integration updates the final values for satellite position and velocity, using drag and gravity coefficients from the history tape, to obtain starting values for the current two-day period. The second integration utilizes these computed starting values to compute the trajectory for the current two-day period. The integrations are performed using Cowell's formula and a predictor-corrector method. Cowell's integration formulas are used in the following form:

$$\dot{x}_n = \frac{1}{\Delta t}[\nabla^{-1}(\Delta t^2 f_{n-1}) + \sum_{j=o}^{m} a_j \nabla^j(\Delta t^2 f_n)], \text{ and}$$

$$x_n = \nabla^{-2}(\Delta t^2 f_{n-1}) + \sum_{j=o}^{m} c_j \nabla^j(\Delta t^2 f_n),$$

where

$x, \dot{x}$ = satellite position and velocity at time n,

Δt = integration interval (60 seconds, currently),

f_n = value of equations of motion (acceleration) at time n,

m = order of integration,

$\nabla^i(h)$ = i^{th} backward difference; i = -2, -1, ...m,

a_j, c_j = Cowell coefficients.

The predictor-corrector process is repeated to get values at 120-second intervals for the current two-day period. Lagrangian interpolation is then used to get x and $\dot{x}$ at the exact observation times. The trajectory tape is then used as a reference for filtering the observed data.

c) Observation Filtering--To filter out bad observations, a frequency which would be expected from a satellite in the orbit calculated above is computed for each observation time. The frequency, f_c, is computed as follows:

$$f_c = \frac{-f_s}{c}\left(\left|\vec{r_j} - \vec{r_o}\right|^{\cdot}\right) + C_{TR} + C_{SP} ,$$

where

f_s = nominal satellite oscillator frequency,

c = adopted value of speed of light in a vacuum (2.997925 x 10^8 m/sec.),

$\left|\vec{r}_j - \vec{r}_o\right|^{\cdot}$ = change in velocity of slant range vector,

C_{TR} = tropospheric refraction correction term,

C_{SP} = satellite position correction for propagation delay.

Residuals for the two-day period are calculated by subtracting these computed frequencies from the observed frequencies on the ASTRO Unsampled Observation Tape, i.e., $(f_o - f_c)$. The tropospheric refraction correction is computed solely for the filtering process. It is not applied to the observed data.

Part of the magnitude of the residuals is due to the difference between the observed and computed orbits. Therefore, the residuals are minimized through a least squares solution by fictitiously moving the station position along two vectors:

(i) The vector from station to satellite at closest approach

(ii) The vector at the station parallel to satellite velocity vector at closest approach

A straight line fit to the minimized residuals is then computed for an entire pass. Observations having residuals which are greater than 2.5 times the rms of all the residuals are tagged for deletion. The station coordinate solution and filtering process is then iterated until no additional observations are deleted.

The remaining observations are then aggregated in groups of eight, covering a 32-second interval. A smoothed frequency value is calculated by fitting a straight line to the residuals in the 32-second interval, and evaluating the fit at the central time of the interval. The residual corresponding to the fit at the central time is then added to the computed frequency for that time. This gives a smoothed frequency which represents the entire 32-second interval. The standard deviation of the straight line fit is computed, and its inverse is assigned as the weight of the aggregated observation.

The above procedure is repeated for each pass of the satellite during the two day period.

d) Pass Filtering--Tests are next made to determine if an entire pass may be bad. This is done by comparing each component of the correction to station position across passes. The standard deviation of the corrections in slant range for all passes is computed and any pass whose correction departs from the mean by more than 2.5 times the standard deviation is rejected. A similar test is run for corrections to the velocity vector component. Deviations less than 100 meters are allowed, even if they exceed 2.5 times the standard deviation.

10. An ASTRO Sampled Observation Tape contains essentially the same data as the ASTRO Unsampled Observation

Tape (see Par. 8) except that the data on this tape is filtered.

11. The ASTRO Sampled Observation Tape is then run through a reformat program which arranges the filtered data into that format required by the GSDS. All frequency measurements are scaled to 108 megacycles by multiplying by $\frac{108 \times 10^6}{f_o}$, where f_o is the station oscillator reference frequency. This is done to provide uniformity among the Doppler frequencies obtained from various transmitted frequencies. The required format is shown in APPENDIX D.

12. The properly formatted tape is submitted to the GSDS.

5.22 <u>Corrections to Data</u>

5.221 The following corrections are applied to TRANET Doppler data during preprocessing:

1. Calibration Correction

Calibration corrections are applied to both the time and frequency signals. The values of the corrections are determined by the APL Time and Frequency Facility through continuous VLF frequency comparisons and daily time checks of satellite timing. A hand portable precision clock is used to relate the APL time reference to those at the National Bureau of Standards and the Naval Observatory. The accuracy of this synchronization is within a few microseconds.

Once the values of the calibration corrections are determined, these are sent to the respective stations so that they may be included in their data transmissions. A value for both the frequency and time correction appears in the header of the received paper tape (see APPENDIX E). The corrections are added algebraically to the measured values during preprocessing, as shown in paragraph 7, Section 5.21.

2. Propagation Delay

A correction is made, when applicable, for the propagation delay of the standard time broadcasts (WWV, WWVH, and so forth), by including the value of the propagation delay in the time correction, which appears in the header of the received data. The application of the time correction during preprocessing therefore will account for both calibration error and any propagation delay applied. However, stations generally use these broadcasts for clock control only in emergencies; their conventional control being satellite time signals. Therefore, the propagation delay correction is seldom relevant.

3. Ionospheric Refraction Correction

As described in Section 5.12, first order ionospheric refraction is corrected by analog means at the receiving station by combining the two phase coherent frequencies received from the satellite. To a first approximation, the ionospheric refraction varies inversely with the square of the frequency. By measuring the apparent Doppler shift at each of the two frequencies, the effects of first order refraction are eliminated by use of the following formula for the corrected Doppler shift:

$$\Delta f_D \left(\frac{f_2^{\,2} - f_1^{\,2}}{f_2 \, f_1}\right) = \Delta f_2 - \left(\frac{f_1}{f_2}\right) \Delta f_1 \, ,$$

where

Δf_D = Doppler shift corrected for first order ionospheric refraction,

f_1 = lower frequency of coherent pair,

f_2 = higher frequency of coherent pair,

Δf_1, Δf_2 = measured Doppler shifts in the respective frequencies.

For a frequency pair of 162 Mc./324 Mc.;

$$\frac{3}{2} \Delta f_D = \Delta f_2 - \frac{\Delta f_1}{2} \, .$$

The refraction error is computed during the same operation by the following:

$$\Delta f_I \left(\frac{f_2^2 - f_1^2}{f_2^2}\right) = \Delta f_1 - \left(\frac{f_1}{f_2}\right) \Delta f_2 \, , \quad ,$$

where

Δf_I = Doppler shift due to first order ionospheric refraction.

For frequencies of 162 Mc./324 Mc.:

$$3/4 \; \Delta f_I = \Delta f_1 - \frac{\Delta f_2}{2} \, .$$

5.222 The following correction remains to be applied to TRANET Doppler data deposited in the GSDS.

1. Tropospheric Refraction Correction

The derivation for a tropospheric refraction correction is given in [Hopfield, 1963]. Only the following basic equations are stated here:

$$\Delta f_{tro} = \frac{-f}{c}\frac{d(\Delta s_{tro})}{dt}$$

where

Δf_{tro} = tropospheric refraction correction which is applied to the observed Doppler shift for each data point,

f = satellite transmitter frequency,

c = speed of light,

Δs_{tro} = range error in received signal due to tropospheric refraction.

In application of the correction, use is made of the geometry of a preliminary orbit and an assumed refractivity profile. Simplifying assumptions are listed in the above reference. These are used to get the following expression for the surface refractivity, N_o:

$$N_o = \frac{77.6}{T}\left[P + \frac{4810e}{T}\right],$$

where

T = temperature in degrees Kelvin,

P = surface pressure in millibars,

e = partial pressure of water vapor in millibars.

An analysis of tropospheric refraction errors may also be found in [Newton, 1967a].

5.3 DISCUSSION

Navy Doppler data currently in the GSDS consists of smoothed frequency measurements taken at 32 second intervals. As was previously mentioned, this data contains a refraction error due to tropospheric effects and higher order ionospheric effects. The user may correct for tropospheric effects using a refraction model of his choice; however, more explanation is needed concerning the residual ionospheric refraction. The total correction for effects of the ionosphere would be of the following form [Guier, et al., 1965]:

$$f = \Delta f_v + \frac{a_1}{f} \pm \frac{a_2}{f^2} + \frac{a_3}{f^3} + \text{higher order terms,}$$

where

Δf_v = Doppler shift in a vacuum.

The first order term, $\frac{a_1}{f}$, is proportional to the time derivative of the electron density integrated along the slant range vector to the satellite. This is corrected at the tracking station.

The term $\frac{a_2}{f^2}$, is the Faraday term which is proportional to the time derivative of the integral of electron density and a component of the earth's magnetic field. This can be considered negligible.

The third order term depends on higher powers of the electron density and its spatial gradient. This can be considered non-negligible during periods when either the electron density or its gradient is large. This phenomenon should occur during the next three years since the sunspot cycle will be a maximum.

The first order refraction term is by far the largest and the estimated error involved in neglecting the other terms is 3 meters under normal ionospheric conditions. One method of reducing refraction errors is through the use of higher frequencies. This will shortly be accomplished with GEOS B transmitting on 972 Mc., along with the present frequencies of 162 Mc. and 324 Mc. Although three or more frequencies can be used to reduce the ionospheric refraction error, it is probably simpler, when the data are used only for satellite tracking, to use two higher frequencies. It is expected that the use of the 324/972 Mc. pair will reduce the ionospheric contribution to less than one meter even at maximum ionospheric activity [Newton, 1967b].

The resultant of observational errors in the system is about 10 meters for the data from one pass. Most of the observational errors are random and their effect can presumably be decreased by the use of a large volume of data. All known observational errors have been analyzed in [Newton, 1967a].

6. RECOMMENDATIONS AND CONCLUSIONS

Since the purpose of this report was to accurately document the preprocessing procedures currently used by various agencies, this research could provide the basis for future analyses of procedures and corrections applied to data. One area of investigation which could lead to important conclusions is the comparison of refraction models used by the various agencies in the reduction of satellite data. A better refraction model would obviously lead to more accurate data in the Geodetic Satellites Data Service. Work in this area is currently being done at Goddard Space Flight Center and at The Ohio State University.

There are several recommendations which can be made with respect to data that is submitted to the GSDS. These recommendations pertain mostly to the format required for submission, as outlined in the GEOS Mission Plan. They consist of the following:

1. The GEOS Mission Plan specifies that submitted data will be accompanied by supplemental reports. These reports are to indicate the corrections applied to the data during preprocessing, along with other pertinent information which may aid the investigator in the application of data from the GSDS. These reports have never been submitted,

which presents a great handicap to the accurate utilization of the data. A publication should be available to all who utilize the data deposited in the GSDS. The booklet should contain specific corrections used in preprocessing the data, corrections recommended to be made by the user, and any other pertinent information. Once published, the information contained therein should be frequently verified and updated.

2. The GSDS format currently specified should be amended to include codes for SAO Laser data (columns 60-63) and future data coming from other equipment such as the GEOCEIVER.

3. The current format specifies including the (D1-IC) value for SECOR observations. If the two-frequency data is not available (as is often the case), there is no way to indicate the modeled ionospheric refraction correction for SECOR.

4. Some systems, such as GRARR and SAO Laser, are planning to record temperature, pressure, and humidity at the tracking stations and use this information to calculate more accurate corrections for tropospheric refraction. The GSDS format should include the readings for temperature, pressure, and humidity.

Work is currently being done to determine a better format for data obtained in the future. Data from GEOS B will be submitted in accordance with the new format which will include codes for the C-Band Radar system, and will give more information about the presently used systems. Many improvements should be made as a result of lessons learned from the data submitted from GEOS-A.

Another recommendation can be made concerning the definition of the reference point in range measurements. Although a displacement correction is given for the GRARR and laser systems, it is presently unclear from which point a range is actually measured, especially for SECOR. A difference of several meters is involved in the difference between the focal point of the antenna and its axis of rotation, or a point on its dish. Any of these points could be the actual point of measurement and a displacement correction should be applied to reference the measured range to a recoverable point on the ground.

A question also arises concerning the necessity of requiring a common data format from all tracking systems. The advantage of a common format is somewhat doubtful when weighed against the additional expense and effort required to reformat the data. There is also an unnecessary delay in data availability due to reformat procedures. If an agency is the sole supplier of data from a certain system, such as SECOR, the same amount of information could be obtained sooner by the investigators if they received the data directly from AMS, in its own format. An alternative might be to deposit data from the various agencies in the GSDS in its original operational format, which could be published for the information of investigators.

There are no error models currently adopted for the various systems, although some provisional error models may result from intercomparison testing being conducted by NASA. Error models for ranging systems and range rate systems have been recommended by D. Brown Associates [Brown, 1965]. These serve as useful starting points for future error analysis and consist of the following:

A. Ranging Channels (SECOR, GRARR, Laser)

$$\delta R = a_1 + a_2\tau + a_3 R + a_4\dot{R} + a_5 \csc E + a_6 \csc^3 E + a_7 \frac{X - X^c}{R} + a_8 \frac{Y - Y^c}{R} + a_9 \frac{Z - Z^c}{R},$$

where

$\tau = t - t_o$ = time relative to time t_o of arbitrary epoch established near center of pass,

$R, \dot{R}$ = range and range rate,

E = elevation angle of satellite above plane tangent to earth at tracker,

X, Y, Z = coordinates (nominal) of satellite in master frame,

X^c, Y^c, Z^c = coordinates (nominal) of ranging station.

The coefficients represent

a_1 = ranging zero set error,

a_2 = phase drift,

a_3 = range scaling error or frequency bias,

a_4 = timing bias,

a_5, a_6 = first and second order residual refraction,

a_7, a_8, a_9 = X, Y, Z components of survey error.

B. Range Rate Channels (Tranet, GRARR)

$$\delta\dot{R} = a_2 + a_3\dot{R} + a_4\ddot{R} + a_5(-\dot{E} \csc E_{ij} \text{ ctn } E_{ij})$$
$$+ a_6(-3\dot{E} \text{ ctn}E \csc^3 E)$$
$$+ a_7 (R\dot{X} - (X-X^c) \dot{R})/R^2$$
$$+ a_8 (R\dot{Y} - (Y-Y^c) \dot{R})/R^2$$
$$+ a_9 (R\dot{Z} - (Z-Z^c) \dot{R})/R^2 ,$$

where in addition to quantities defined in ranging error model;

$\dot{E} = \frac{dE}{dt}$ = rate of change of elevation angle,

X^c, Y^c, Z^c = coordinates (nominal) of tracker,

E_{ij} = elevation angle of supplemental antenna.

In case of Tranet, the following additional term is recommended to be provisionally included in the error model:

$a_o \ (R+\dot{R}\tau)$,

where

a_o = short term (15 min) combined frequency drift of satellite oscillator and ground station oscillator.

The provisional <u>a priori</u> constraints on error coefficients, according to Brown, are

$\sigma a_o = 10^{-8}$ (underconstrains a_o by an order of magnitude),

σa_1 = 10 meters (SECOR, Laser) = 25 meters (GRARR),

σa_2 = .01 m/sec.,

$\sigma a_3 = 5 \times 10^{-6}$,

σa_4 = .001 sec.,

σa_5 = 0.3 m,

$\sigma a_6 = 0.01$ m,

σa_7, a_8, $a_9 < 10$ m for most first order stations on NAD.

The current work being done by NASA in the Observation Systems Intercomparison Investigation should make great strides toward determining the relative accuracy of the respective systems. Once the accuracy of a system is known, better preprocessing procedures can be developed to obtain data which can be used with confidence in all geodetic applications.

APPENDIX A

GSDS FORMAT FOR ELECTRONIC AND LASER RANGE OBSERVATIONS

Field	Cols.	Description
1.	1 - 6	Satellite Identification*
	1 - 2	Year of Launch
		64 = 1964
		65 = 1965
		66 = 1966
		etc.
	3 - 5	Order of Launch
	6	Component Identifier
		1 = a
		2 = b
		3 = c
		4 = d
		etc.
2.	7	Type of Coordinates
		1 = Right Ascension and Declination
		2 = Range
		3 = Range Rate

*As per COSPAR numbering system.

Field	Cols.	Description
		4 = Frequency Shift
		5 = Direction Cosines
		6 = X, Y, Angle
		7 = Azimuth and Elevation Angle
3.	<u>8</u>	<u>Observation Identifier</u>
		8 = Electronic Range
		9 = Laser Range
4.	<u>9 - 11</u>	<u>Timing Standard Deviation</u>
	9	Milliseconds
	10 - 11	.01 Milliseconds
5.	<u>12 - 13</u>	<u>Time Identifier</u>
		00 = UT-0 determined at observing station
		01 = UT-1 determined at observing station
		02 = UT-2 determined at observing station
		03 = UT-C determined at observing station
		04 = A.1 determined at observing station
		05 through 49 Other Systems*
		50 = UT-0 Satellite time
		51 = UT-1 Satellite time

*As described in the associated preprocessing report; number assigned at NSSDC before transmitting data to various investigators.

APPENDIX A (Cont'd.)

Field	Cols.	Description	
		52 = UT-2	Satellite time
		53 = UT-C	Satellite time
		54 = A.1	Satellite time
		55 through 99	Other Systems*
6.	<u>14 - 18</u>	<u>Station Number</u>	
	14	System Designator	
		0 = COSPAR	
		1 = AFCRL	
		2 = SAO	
		3 = STADAN	
		4 = TRANET DOPPLER	
		5 = AMS	
		6 = USC-GS	
		7 = Naval Observatory	
		8 = International Participants	
	15 - 18	Station Number	
7.	<u>19 - 34</u>	<u>GMT of Observation</u>	
	19 - 20	Year of Observation	
		64 = 1964	
		65 = 1965	
		66 = 1966	
		etc.	

*As described in the associated preprocessing report; number assigned at NSSDC before transmitting data to various investigators.

APPENDIX A (Cont'd.)

Field	Cols.	Description
	21 - 22	Month of Observation
	23 - 24	Day of Observation
	25 - 26	Hour of Observation
	27 - 28	Minute of Observation
	29 - 30	Second of Observation
	31 - 34	.0001 Second of Observation
8.	<u>35 - 53</u>	<u>Observation Data</u>
	35 - 50	Range in Meters
	51 - 53	Range in .001 Meters
9.	<u>54 - 59</u>	<u>Date of Reduction</u>
	54 - 55	Year of Reduction
		64 = 1964
		65 = 1965
		66 = 1966
		etc.
	56 - 57	Month of Reduction
	58 - 59	Day of Reduction
10.	<u>60 - 64</u>	<u>Coded Information</u>
	60 - 61	Supplementary Documentation
		01 = AMS SECOR Preprocessing Report
		07 = NASA Goddard Range and Range Rate Preprocessing Report
		09 = NASA Goddard Laser Preprocessing Report
		10 = AFCRL Laser Preprocessing Report

APPENDIX A (Cont'd.)

Field	Cols.	Description
	62 - 63	Instrumentation Type
		61 = AMS SECOR System
		62 = GSFC Range and Range Rate System
		63 = GSFC Laser System
		64 = AFCRL Laser System
	64	Tropospheric Correction
		1 = Tropospheric Refraction Correction Applied
		2 = Tropospheric Refraction Correction Not Applied
11.	<u>65 - 70</u>	<u>Description of Random Error</u>
	65 - 67	Standard Deviation in Meters
	68 - 70	Standard Deviation in .001 Meters
12.	<u>71 - 77</u>	<u>Ionospheric Correction</u>
	71 - 76	Meters, XXX.XX (Dl-IC for SECOR)
	77	Application
		1 = Correction Applied to Measurement
		2 = Correction Not Applied to Measurement
13.	<u>78</u>	<u>Quality</u> (SECOR Only)
		0 = Data appears Normal
		1 = Data Noisy
		2 = Data Possibly Ambiguous
		3 = Data Noisy and Possibly Ambiguous
		4 = Data not Acceptable to AMS

APPENDIX A (Cont'd.)

Field	Cols.	Description
14.	79	Solution Code (SECOR Only)
		0 = Used in Solution by AMS
		1 = Not Used in Solution by AMS
		2 = Rejected from Solution by AMS
15.	80	Blank

(Columns 78 and 79 are currently blank for ranging systems other than SECOR.)

APPENDIX B

EXPLANATION OF GRARR TELETYPE DATA

1. The following is a description of the received teletype data from GRR-1 (see Figure 3.3a).

C1--Ambiguity and Resolution Switch

The C1 control digit specifies the lowest sidetone (ambiguity) and the highest sidetone (resolution) used in the range measurement for that frame as follows:

C1 DIGIT	AMBIGUITY (cps)			RESOLUTION (Kc.)		
	160	32	8	20	100	500
1			1	1		
2			1		1	
3			1			1
4		1		1		
5		1			1	
6		1				1
7	1			1		
8	1				1	
9	1					1

C2--Recording Rate and Punch Indicator

Two paper tape punches are used to punch identical data for all recording rates except 8 samples per second. In this case, each punch records at 4 samples per second with punch 1 recording the first, third, fifth, and seventh measurements; punch 2 recording the second, fourth, sixth, and eighth measurements. In punch 2 there is a lag of .125 sec. from the data frame time. The recording rate also determines the cycles to be counted for range rate measurement (see TABLE 4).

C2 DIGIT	PUNCH NUMBER		RECORDING RATE (sample/sec.)			
	1	2	1	2	4	8
0	1		1			
1	1			1		
2	1				1	
3	1					1
4		1	1			
5		1		1		
6		1			1	
7		1				1

C3--Frequency Indicator

The C3 control digit specifies the uplink carrier frequency, and the bias frequency for range rate measurement as follows:

C3 DIGIT	S-BAND			VHF	BIAS FREQUENCY (Mc.)	
	A	B	C		.500	.030
0	1				1	
1		1			1	
2			1		1	
3				1		1

where the uplink frequencies are

A = 2271.9328 Mc.,
B = 2270.9328 Mc.,
C = 2270.1328 Mc.,
VHF = 148.2600 Mc.

C4--Range Counter Frequency

The C4 control digit specifies the range counter frequency used in the range extraction unit to measure the total transit time of the ranging tones.

APPENDIX B (Cont'd.)

C4 DIGIT	RANGE COUNTER (Mc.) 10	100
0	1	
1		1

X-angle

The X-angle can vary from 0 degrees to ± 90 degrees. The angle is positive when east of the meridian of the tracking station; negative when west. The meridian is the zero degree line.

Y-angle

The Y-angle varies from 0 degrees to ± 90 degrees. The angle is zero when at the zenith. It is positive north of the zenith and negative to the south.

2. The following is a description of the received teletype data from GRR-2 (see Figure 3.3b).

Q--Data Quality Indicator

This digit can contain any of the following symbols:

Q DIGIT	FAILURE	DATA AFFECTED
Blank	None	None
?	Two or more of the following failures	All
0	Receiver Carrier Loop	All
1	Receiver Subcarrier	Range, Range Rate
2	Antenna not on Auto-track	X- & Y- Angles
3	Digital range tone extractor not locked	Range

It is recommended [Sapper, 1967] that

a) For indicators of ?, 0, 1; discard entire data frame,

b) For indicator of 2, discard X- and Y-angles,

c) For indicator of 3, discard only the immediately following range.

B--Data Quality or Range Rate Digit

This digit will be a data quality indicator, with meaning shown above, except when the C2 digit is a 3 or 7, i.e., when data rate is 6 per minute. In this case the B digit will be the integer part of the range rate data. The new range rate measurement would then be $B.\dot{R}\dot{R}\dot{R}\dot{R}\dot{R}\dot{R}\dot{R}$.

C1--Frequency Indicator

The C1 control digit specifies the uplink carrier frequency, and the bias frequency for range rate measurement as follows:

C1 DIGIT	S-BAND A	S-BAND B	S-BAND C	VHF	BIAS FREQUENCY (Mc.) .500	BIAS FREQUENCY (Mc.) .030
0	1				1	
1		1			1	
2			1		1	
3				1		1

where the uplink frequencies are

A = 2271.9328 Mc.,
B = 2270.9328 Mc.,
C = 2270.1328 Mc.,
VHF = 148.2600 Mc.

C2--Recording Rate Indicator and Resolution Switch

Only one punch is used in the GRR-2 system, since the recording rate of 8 samples/sec. is not used. The recording rate determines the cycles to be counted for range rate measurement (see TABLE 4). The recording rate and highest sidetone used (resolution) are specified as follows:

C2 DIGIT	RESOLUTION 20 Kc	RESOLUTION 100 or 500 Kc	RECORDING RATE 1/s	RECORDING RATE 2/s	RECORDING RATE 4/s	RECORDING RATE 6/m
0	1		1			
1	1			1		
2	1				1	
3	1					1
4		1	1			
5		1		1		
6		1			1	
7		1				1

N1 and N2--Range Ambiguity Numbers

Since ambiguity occurs at each period of the lowest ranging sidetone used, the range ambiguity resolution system counts the number, N, of periods of the lowest sidetone. A table containing values of ambiguities for various values of N may be found in APPENDIX C.

If N1 and N2 are blank, the hybrid range ambiguity resolution system is not in use. In this case, determine N from the above-mentioned table, assuming an approximate orbital range is known.

If N1 and N2 are question marks (??) the hybrid system is in use but the range ambiguity resolution system is not in lock. Determine N as above.

If N1 and N2 are integers, N should not be determined as above, but from the following equation:

$$N = 10N1 + N2.$$

The lowest ranging sidetone used is usually the

APPENDIX B (Cont'd.)

8 cps sidetone.

X-angle

The X-angle varies from 0 degrees to $\pm$ 90 degrees. The angle is zero when on the meridian of the tracking station. It is positive east of the meridian and negative to the west.

Y-angle

The Y-angle varies from 0 degrees to $\pm$ 90 degrees. The angle is zero at the zenith. It is positive north of the zenith and negative to the south.

APPENDIX C

CONVERSION OF GRARR TELETYPE DATA

(re: Section 3.21)

A. The received teletype data is put on magnetic tape in blocks of up to eight frames (16 lines). Provisions are made for a special record in the following format which can be inserted at the beginning of each block:

Column	Contents
1-2	* *
10-12	N (range gate in octal)
13-16	$T_B + T_T$ (four octal characters)

This record is not presently being used.

The process of converting the received time interval measurements to range in meters and range rate in meters per second consists of the following four basic steps:

1. Calculate true time of each range sample

a) Calculate the correct two-way propagation time by:

$$T_{RT} = T_R + \frac{N}{F_L} - T_T,$$

where

T_{RT} = correct two-way propagation time,

T_R = measured time interval corresponding to the phase shift between the transmitted and received signal (R in data frame),

N = total number of complete periods of the lowest sidetone frequency used (for GEOS-A, N=1),

F_L = frequency of lowest sidetone employed in range measurement, which is determined from C1 (GRR-1) or is usually 8 cps for GRR-2,

T_T = effective transponder delay = $T_D - T_P$,

where

T_D = satellite transponder delay,

T_p = Pole beacon simulator delay.

The value of T_T will vary for each satellite and is obtained from tests made prior to launch by the Network Engineering Branch, GSFC. For GEOS-A, T_T for channel A = 3.5 microseconds and T_T for channel C = 3.7 microseconds.

b) Calculate time of range measurement by

$$T_{RM} = T_S + T_R - \frac{T_{RT}}{2} + T_W,$$

where

T_{RM} = true time of range sample (time when signal left the satellite),

T_W = WWV signal propagation delay (different for each station),

T_S = time at start of range sample.

$$T_S = T_F + KT_{DR} + \begin{bmatrix} 0 \text{ if } C_2 \neq 7 \\ .125 \text{ if } C_2 = 7 \end{bmatrix},$$

where

T_F = time given in data frame,

T_{DR} = reciprocal of recording rate, which is determined from the C_2 control digit,

K = 0,1,2,3 denotes the 1st, 2d, 3d, or 4th range data sample in each frame, respectively. The last term is used only for the GRR-1 system and compensates for the lag in punch number 2.

By substitution we also get the expression

$$T_{RM} = T_S + 1/2 \ (T_R - \frac{N}{F_L} + T_T) + T_W.$$

2. Calculate range measurement

$$R = \frac{C}{2} \ (T_{RT}) = \frac{C}{2} \ (T_R + \frac{N}{F_L} - T_T),$$

where R = range in meters from station to satellite,

C = velocity of light = 299,792,500 m/sec.

Provision is made in the special record at the beginning of each data block to account for other bias errors, T_B; however, this is not currently being used.

3. Calculate true time of each range rate sample

$$T_{\dot{R}M} = T_S + \frac{T_{\dot{R}}}{2} - \frac{T_{RT}}{2} + T_W ,$$

where

$T_{\dot{R}M}$ = time of range rate measurement,

$T_{\dot{R}}$ = time required to count N_F cycles of the two-way Doppler plus bias frequency (see TABLE 4). This is given as $\dot{R}$ in data frame.

We can also write

$$T_{\dot{R}M} = T_{RM} + \frac{T_{\dot{R}}}{2} - T_R .$$

4. Calculate range rate measurement

$$\dot{R} = \frac{C}{2F_U} \ (B - \frac{N_F}{T_{\dot{R}}}) + \frac{C}{4F_U^2} \ (B - \frac{N_F}{T_{\dot{R}}})^2,$$

where

$\dot{R}$ = range rate measurement in meters per second,

F_U = uplink carrier frequency, which is determined from control digit C3 (GRR-1) or C1 (GRR-2),

B = bias frequency, which is determined from control digit C3 (GRR-1) or C1 (GRR-2).

B. To calculate the true time of the measurement of the X- and Y-angles, T_{xy}, it is necessary only to correct the time given in the data frame for propagation delay by

$$T_{xy} = T_F + T_W.$$

C. The following table gives the value of the range in meters which corresponds to each period of the lowest sidetone specified.

N	F_L 8 cps	32 cps	160 cps
1	18,737,031.3	4,684,257.8	936,851.6
2	37,474,062.5	9,368,515.6	1,873,703.1
3	56,211,093.8	14,052,773.4	2,810,554.7
4	74,948,125.0	18,737,031.2	3,747,406.2
5	93,685,156.3	23,421,289.1	4,684,257.8
6	112,422,187.5	28,105,546.9	5,621,109.4
7	131,159,218.8	32,789,804.7	6,557,960.9
8	149,896,250.0	37,474,062.5	7,494,812.5
9	168,633,281.3	42,158,320.3	8,431,664.1
10	187,370,312.5	46,842,578.1	9,368,515.6

APPENDIX D

GSDS FORMAT FOR RANGE RATE OBSERVATIONS

Field	Cols.	Description
1.	1 - 6	Satellite Identification*
	1 - 2	Year of Launch
		64 = 1964
		65 = 1965
		66 = 1966
		etc.
	3 - 5	Order of Launch
	6	Component Identifier
		1 = a
		2 = b
		3 = c
		4 = d
		etc.
2.	7	Type of Coordinates
		1 = Right Ascension and Declination
		2 = Range
		3 = Range Rate

*As per COSPAR numbering system.

Field	Cols.	Description
		4 = Frequency Shift
		5 = Direction Cosines
		6 = X, Y, Angle
		7 = Azimuth and Elevation Angle
3.	8	Observation Identifier
		5 = Base Frequency
		6 = Observed Frequency
		7 = Range Rate in meters/second
4.	9 - 11	Timing Standard Deviation
	9	Milliseconds
	10 - 11	.01 Milliseconds
5.	12 - 13	Time Identifier
		00 = UT-0 determined at observing station
		01 = UT-1 determined at observing station
		02 = UT-2 determined at observing station
		03 = UT-C determined at observing station
		04 = A.1 determined at observing station
		05 through 49 Other Systems*

*As described in the associated preprocessing report; number assigned at NSSDC before transmitting data to various investigators.

APPENDIX D (Cont'd.)

Field	Cols.	Description	
		50 = UT-0	Satellite time
		51 = UT-1	Satellite time
		52 = UT-2	Satellite time
		53 = UT-C	Satellite time
		54 = A.1	Satellite time
		55 through 99 Other Systems.	
6.	<u>14 - 18</u>	<u>Station Number</u>	
	14	System Designator	
		0 = COSPAR	
		1 = AFCRL	
		2 = SAO	
		3 = STADAN	
		4 = TRANET DOPPLER	
		5 = AMS	
		6 = USC+GS	
		7 = Naval Observatory	
		8 = International Participants	
	15 - 18	Station Number	
7.	<u>19 - 34</u>	<u>GMT of Observation</u>	
	19 - 20	Year of Observation	
		64 = 1964	
		65 = 1965	
		66 = 1966	
		etc.	

APPENDIX D (Cont'd.)

Field	Cols.	Description
	21 - 22	Month of Observation
	23 - 24	Day of Observation
	25 - 26	Hour of Observation
	27 - 28	Minute of Observation
	29 - 30	Second of Observation
	31 - 34	.0001 Second of Observation
8.	35 - 53	Observation Data
	35 - 50	Cycles per second or meters per second
	51 - 53	.001 cycles per second or .001 meters per second
9.	54 - 59	Date of Reduction
	54 - 55	Year of Reduction 64 = 1964 65 = 1965 66 = 1966 etc.
	56 - 57	Month of Reduction
	58 - 59	Day of Reduction
10.	60 - 66	Coded Information
	60 - 61	Supplementary Documentation 02 = NWL Doppler Preprocessing Report 07 = NASA Goddard Range and Range Rate Preprocessing Report

APPENDIX D (Cont'd.)

Field	Cols.	Description
	62 - 63	Instrumentation Type
		51 = TRANET Doppler System
		52 = Goddard Range and Range Rate System
	64	Tropospheric Refraction Correction
		1 = Correction Applied
		2 = Correction Not Applied
	65 - 66	Identification of Frequency Pair and Method of Combination (see associated preprocessing report)
11.	<u>67 - 74</u>	<u>Value of C</u>
	67	Kilometers per second (first five digits assumed)
	68 - 69	.01 Kilometers per second
	70 - 74	Uncertainty in C, X.XXX Kilometers/ sec.
12.	<u>75 - 77</u>	<u>Description of Random Error</u>
	75 - 77	Standard Deviation in frequency shift, .001 cycles/second or standard deviation in range rate, .001 meters/second .
13.	<u>78 - 80</u>	<u>Blank</u>

APPENDIX E

DESCRIPTION OF TRANSMITTED DOPPLER DATA

Figure 5.5 represents a postion of the IBM 1009 data tape transmitted to NWL. The first line is a header message; the second line is a narrative mesage; the third signifies the end of data. The fourth line is a new header message; the next group of lines is a data message, and the last line signifies end of data.

The following is a description of the specific portions of the data:

A. Header Format

The following descriptions appear in the same order, left to right as the groups of digits in the header of Figure 5.5.

1) APL Format Control--Determines format structure of message.

2) APL Station Number Code--Specifies the station which recorded the data.

3) APL Satellite Number--Specifies the satellite from which the data was observed.

4) Q Pair Code--These three digits state, by means of an adopted convention, the satellite transmitted frequencies and the effective frequency after the refraction

correction is applied.

The convention for the statement of the Q pair is as follows:

Digit 1 = the first nominal frequency observed on the pass.

Digit 2 = the second nominal frequency observed on the pass.

Digit 3 = the effective combined frequency after the refraction correction has been accomplished. This applies to the vacuum Doppler solution for the refraction system used.

Frequency Pair (Mc.)	Refraction Correction System	Effective Frequency (Mc.)	Q
54/162	APL Model 3	144	133
54/162	NACODE	144	133
54/216	APL Model 3	202.5	141
54/216	NACODE	202.5	141
54/324	APL Model 3	315	151
54/324	NACODE	315	151
162/216	NACODE	94.5	342
162/216	APL Model 3	31.5	344
162/324	APL Model 3	243	351
162/324	NACODE	243	351
216/324	APL Model 3	90	451
216/324	NACODE	180	453
150/400	APL Model 3	114.5833	261
150/400	AN/BRN-3 (OPTRAC)	687.5	265
150/400	NACODE	343.75	266
324/972	APL Model 3	432	591
324/972	NACODE	864	593

5) Observation Year--Last two digits of year (63 = 1963. 6) Observation Day--Day of year counting from first day (001 = Jan. 1).

7) Rise Time--The rise time of the pass is given in hours and minutes, Greenwich Mean Time (1236 = $12^h\ 36^m$).

8) First Time of Pass--Time of first observation. This is no longer used.

9) Last Time of Pass--Time of last observation. This is no longer used.

10) Station Time Clock Error (Δt_c)--Represents the difference in seconds between the system standard time (UTC) and the station clock. This includes the propagation delay, if applicable. The decimal point is understood to precede the first digit.

11) Frequency Standard Correction (Δf_o)--Represents the bias in the station oscillator frequency standard, in cycles per second. The decimal point is understood to precede the first digit. Algebraic signs correspond to the convention: (Station frequency standard -Reference frequency standard) where a plus sign is represented in the header by the symbol "&."

12) Number of Beat Cycles Counted (n_c)--Represents the actual number of beat cycles preset in the digitizer counter at the station.

13) Time and Frequency Standard--Represents a coded designation of the standards used by the station. The first digit is the time standard code and the second is the frequency standard code, according to the following

table:

Time Standard (1st digit)	Frequency Standard (2nd digit)
0 =	0 = Frequency derived from time standard
1 = WWV	1 = NAA
2 = WWVH	2 = NBA
3 =	3 = NPG/NLK
4 = MSF	4 = OMEGA
5 = JJY	5 = GBR/GBZ
6 =	6 = NPM
7 = ZUO	7 = WWVL
8 = Satellite	8 = NSS
9 = Other	9 = Other

14) Indicator--A "*" indicates a narrative message follows. A "=" indicates a data message follows.

B. Data Format

Each group of eleven digits in this section consists of a value for the time, t, when the beat cycle count was initiated and the time interval, T, required to count n_c beat cycles; according to the following format:

XXXX XXXXXXX

t T

The value of t is given in seconds without the highest order digit which is later computed from the value of the Rise Time. The value of T is also given in seconds with the decimal point as shown.

Occasionally a satellite time point is inserted into the data, replacing the time interval measurement (see Figure 5.4). This is indicated by a zero in the fifth digit, which acts as a flag. The six digits foll zero make up the satellite timing point in micros with the unit microseconds digit immediately foll zero. This is shown below.

$$\underbrace{XXXX}_{t}\ 0\ \underbrace{XXXXXX}_{(1\ -\Delta t)\ \text{in tens of microsecon}}$$

0 → unit microseconds part of (1 $-\Delta$t)

Example: The data point 13240631244 indi that a satellite marker was recognized at 312.446 seconds before ( )1325 seconds, or 687.554 millis after ( )1324 seconds. The missing seconds digit tained from the Rise Time in the header.

C. Logical Record

The word LOGRCD signifies the end of t

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digit, which acts as a flag. The six digits following the zero make up the satellite timing point in microseconds, with the unit microseconds digit immediately following the zero. This is shown below.

$$\underbrace{XXXX}_{t}\;\underset{\Big\downarrow}{0}\;\underbrace{XXXXXX}_{(1-\Delta t)\text{ in tens of microseconds.}}$$

unit microseconds part of $(1 - \Delta t)$

Example: The data point 13240631244 indicates that a satellite marker was recognized at 312.446 milliseconds before ( )1325 seconds, or 687.554 milliseconds after ( )1324 seconds. The missing seconds digit is obtained from the Rise Time in the header.

C. Logical Record

The word LOGRCD signifies the end of the data.

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